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(71) Applicant: **NIPPON TELEGRAPH AND TELEPHONE CORPORATION**
Shinjuku-ku, Tokyo 163-19 (JP)

(72) Inventors:
- **Kato, Masao, Nippon Telegr. & Teleph. Corp. Tokyo 163-14 (JP)**
- **Kurokawa, Kenji, Nippon Telegr. & Teleph. Corp. Tokyo 163-14 (JP)**
- **Horiguchi, Tuneo, Nippon Telegr. & Teleph. Corp. Tokyo 163-14 (JP)**
- **Miyajima, Yoshiaki, Nippon Telegr. & Teleph. Corp. Tokyo 163-14 (JP)**

(74) Representative: **Pfenning, Meinig & Partner**
Mozartstrasse 17
80336 München (DE)

(54) **Optical fiber**

(57) An optical fiber includes a core, a first cladding, a second cladding, and a third cladding. The core has a refractive index n_0. The first cladding is formed around the core and has a refractive index n_1. The second cladding is formed around the first cladding and has a refractive index n_2. The third cladding is formed around the second cladding and has a refractive index n_3. The refractive indices have relationships $n_1 > n_2 > n_3$ and $n_1 > n_0$.

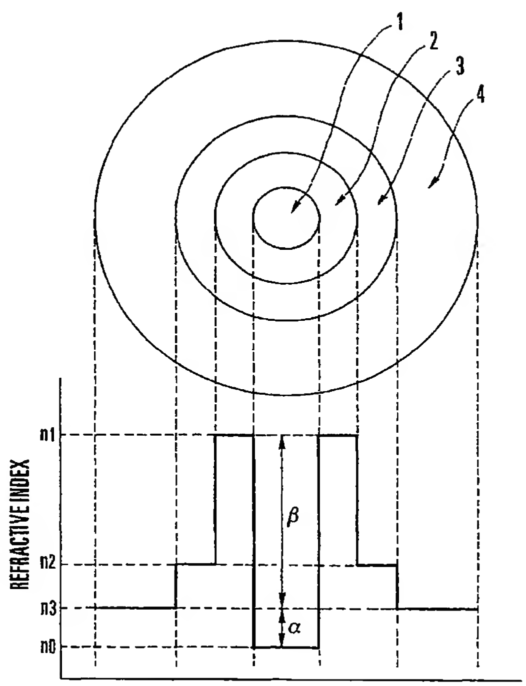

FIG. 1

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Description

Background of the Invention

The present invention relates to an optical fiber.

A silica-based single-mode optical fiber (to be referred to as an SMF (Single-Mode Fiber) hereinafter) which is generally used in optical communication has a wavelength band for giving the minimum transmission loss within the range of 1.4 to 1.6 μm. Such a wavelength band is preferably used for long-distance optical communication. However, when an optical signal having the minimum transmission loss wavelength propagates through the SMF, the waveform degrades due to chromatic dispersion, resulting in limitations on the bit rate and the transmission distance.

The chromatic dispersion in such an optical fiber is given by both material dispersion and waveguide dispersion. For example, in a conventional SMF having a core diameter of 10 μm, whose relative index difference Δ between the core and cladding is 0.3%, material dispersion is more dominant than waveguide dispersion. Since the chromatic dispersion of silica used as a material is reflected to result in a zero-dispersion wavelength in the 1.3-μm band, the SMF used in a wavelength band of 1.5 μm of large-capacity optical communication has a chromatic dispersion of about +17 ps/nm/km.

Note that "+17 ps/nm/km" means that when an optical pulse having a spectral width of 1 nm (FWHM) propagates in a 1-km long optical fiber, the pulse width broadens by about 17 ps ("Nonlinear Fiber Optics", Govind P. Agrawal, p. 63 (Dispersion-induced Pulse Broadening), Academic Press).

Conventionally, demand has arisen for a technique of reducing the limitation on transmission capacity due to chromatic dispersion to increase the bit rate and transmission distance. To meet this requirement, an optical fiber called a dispersion shifted fiber (to be referred to as a DSF (Dispersion Shifted Fiber) hereinafter) has already been developed as an optical fiber having minimum chromatic dispersion in a communication wavelength band of 1.5 μm (Nobuo K. et al., "Characteristics of dispersion-shifted dual shape core single-mode fibers", J.L.T., LT-5, No. 6, p. 792 (1987)).

In this DSF, the index distribution of the core and cladding is designed such that waveguide dispersion has an opposite sign to that of material dispersion but the same absolute value. The zero-dispersion wavelength is set within the 1.5-μm band. To satisfy these conditions, the relative index difference Δ between the core and cladding is set to be 0.7% or more, i.e., the waveguide dispersion is made large. However, when the relative index difference Δ is large, the core diameter must be small to satisfy the single-mode condition (to be described later).

Consequently, the field distribution of light becomes narrow, and the effective core area (to be referred to as an Aeff hereinafter) is smaller than that of the SMF.

The single-mode condition will be described. In case of a step-index fiber, letting λ be the wavelength to be used, a normalized frequency V at the wavelength to be used is given by:

$$V = (2\pi/\lambda)\bullet a\bullet n_1(2\Delta)^{0.5} \quad (1)$$

$$\Delta = (n_1 - n_2)/n_1 \quad (2)$$

where a is the core diameter, n_1 is the refractive index of the core, n_2 is the refractive index of the cladding, and Δ is the relative index difference between the core and cladding. To satisfy the single-mode condition, the value of the frequency V must be 2.405 or less.

When the relative index difference Δ is increased to make the waveguide dispersion large, the core diameter a must be designed to be small instead. However, when the core diameter a is reduced to increase the relative index difference Δ, the light confinement effect in the core increases. The Aeff becomes smaller than that of the SMF, and additionally, the bending loss decreases.

A transmission system with a regenerative repeater spacing of 320 km and a bit rate of 10 Gb/s has already been put into practical use by applying the DSF (Dispersion Shifted Fiber) to the transmission line and an erbium-doped optical fiber amplifier (to be referred to as an EDFA hereinafter) to the repeater device.

As a technique of increasing the transmission capacity, wavelength division multiplexing (to be referred to as WDM hereinafter) has conventionally received a great deal of attention domestically and internationally. With the WDM, a plurality of signal wavelengths can be simultaneously used in one communication optical fiber. This realizes a transmission system having a larger capacity than that of the conventional single wavelength transmission.

As described above, when the DSF is used as the transmission line, the intensity of light in the optical fiber (i.e., optical power per unit area of the fiber section) becomes high because of the small Aeff. On the other hand, along with the increase in intensity of signal light, phenomena called optical nonlinear effects are likely to take place in the optical fiber in general. Especially, the effects are easily induced in the DSF having a high intensity of light.

The optical nonlinear effect which decreases the S/N ratio is a serious problem because it imposes considerable limitations on the bit rate and transmission distance of the transmission system using the DSF. Therefore, an actual transmission system using the DSF must transmit signals while suppressing the gain of the optical amplifier.

However, as the bit rate rises, the time slot per signal bit becomes short. To ensure the received power lev-

el, signal power per bit must be increased. This does not agree with suppression of optical nonlinear effects. To suppress the optical nonlinear effects, transmission power must be reduced to limit the bit rate.

When the WDM is employed to increase the transmission capacity, optical nonlinear effects called four-wave mixing (to be referred to as FWM hereinafter) are induced because of presence of a plurality of wavelengths in the optical fiber, so the bit rate and transmission distance are limited.

In the FWM, the third-order nonlinear optical process causes interference between signal wavelengths to generate new light. As the phase matching condition between wavelengths is satisfied, the FWM generation efficiency increases. For this reason, the FWM is more likely to take place when the signal wavelengths are closer to the zero-dispersion wavelength, and the interval between signal wavelengths is smaller. In the DSF whose zero-dispersion wavelength is within the signal wavelength band, the FWM is more likely to be induced than in the SMF, so the interval between signal wavelengths must be increased. However, since the amplification bandwidth of the EDFA is about several ten nm, a large wavelength interval decreases the number of signal channels to limit the transmission capacity.

The application purpose of the DSF is not limited to the transmission line.

For the further improvement of the transmission system, extensive studies on a high-speed optical switch and wavelength conversion device have also been made. The optical switch and wavelength conversion device perform switching or wavelength conversion using the optical nonlinear effects, unlike the transmission line, so how to induce the optical nonlinear effects is the important problem.

An optical switch and wavelength conversion device which are realized using the DSF in which the optical nonlinear effects readily occur because of the small Aeff have already been reported.

However, at a bit rate of 20 Gb/s or more, electrical signal processing cannot be used, and instead, the optical switch or wavelength conversion device must be used. The DSF to be used for the optical switch or wavelength conversion device must have a length of several ten km because the conversion efficiency is low. In addition, input optical power is required.

Summary of the Invention

It is, therefore, a principal object of the present invention to provide an optical fiber allowing easy design of suppression and enhancement of optical nonlinear effects.

It is another object of the present invention to provide an optical fiber capable of suppressing optical nonlinear effects by lowering the intensity of light in the optical fiber, and suppressing FWM by disturbing the phase matching condition between wavelengths.

It is still another object of the present invention to provide an optical fiber capable of enhancing optical nonlinear effects by increasing the intensity of light in the optical fiber.

In order to achieve the above objects of the present invention, there is provided an optical fiber comprising a core having a refractive index n_0, a first cladding formed around the core and having a refractive index n_1, a second cladding formed around the first cladding and having a refractive index n_2, and a third cladding formed around the second cladding and having a refractive index n_3, wherein the refractive indices have relationships $n_1 > n_2 > n_3$ and $n_1 > n_0$.

With this arrangement, an optical fiber capable of suppressing or enhancing the optical nonlinear effects can be provided. An optical fiber for suppressing the optical nonlinear effects can be used for a transmission line. An optical fiber for inducing the optical nonlinear effects can be used for an optical switch or wavelength conversion device.

Brief Description of the Drawings

Fig. 1 is a view showing the section of an optical nonlinearity suppressing fiber according to the present invention and its index distribution;

Fig. 2 is a graph showing the relationship between chromatic dispersion and a relative index difference a between a core and a third cladding;

Fig. 3 is a graph showing the relationship between chromatic dispersion and a relative index difference β between a first cladding and the third cladding;

Fig. 4 is a graph showing the relationship between the second cladding diameter and chromatic dispersion;

Figs. 5A, 5B, and 5C are graphs showing the relationships between the fiber length and chromatic dispersion;

Fig. 6 is a view showing the arrangement of a transmission line using the optical nonlinearity suppressing fiber shown in Fig. 1 and the relationship between the transmission distance and the optical power level;

Fig. 7 is a view showing the section of an optical nonlinearity suppressing fiber according to the present invention and its index distribution;

Figs. 8A and 8B are graphs showing the relationship between the MFD and the relative index difference a between the core and the third cladding;

Fig. 9 is a graph showing the relationship between the MFD and the ratio of the core diameter to the first cladding diameter;

Fig. 10 is a graph showing the relationship between the chromatic dispersion variation and the FWM generation efficiency;

Fig. 11 is a graph showing the relationship between the fiber length and chromatic dispersion;

Fig. 12 is a graph showing the relationship between

the core diameter and the relative index difference β between the first cladding and the third cladding;

Fig. 13 is a graph showing the relationship between the Aeff and the relative index difference β between the first cladding and the third cladding;

Fig. 14 is a graph showing the relationship between the wavelength and chromatic dispersion; and

Fig. 15 is a graph showing the relationship between the bending radius and the bending loss.

Detailed Description of the Preferred Embodiment

An embodiment of the present invention will be described next with reference to the accompanying drawings.

First, an optical fiber (to be referred to as an optical nonlinearity suppressing fiber hereinafter) which can be used for a transmission line by suppressing optical nonlinear effects will be described.

Fig. 1 shows the section of the optical nonlinearity suppressing fiber and its index distribution. As shown in Fig. 1, to suppress the optical nonlinear effects, the refractive index at the core center of a DSF is lowered. More specifically, the optical fiber of this embodiment is formed from a core 1 having a refractive index n_0, a cladding 2 (to be referred to as a first cladding hereinafter) having a refractive index n_1, a cladding 3 (to be referred to as a second cladding hereinafter) having a refractive index n_2, and a cladding 4 (to be referred to as a third cladding hereinafter) having a refractive index n_3, and the refractive indices have at least relationships $n_1 > n_2 > n_3$ and $n_1 > n_0$. Especially, in this case, to suppress the optical nonlinear effects, the refractive indices are set such that a relationship $n_1 > n_2 > n_3 > n_0$ is established. With this arrangement, the first cladding effectively functions as a core. The field distribution of light spreads in the radial direction of the optical fiber to increase the Aeff, so the optical nonlinear effects can be suppressed.

Such an optical nonlinearity suppressing fiber is made of the same material (e.g., silica) as that of the conventional optical fiber although the intensity of light lowers, so the optical nonlinearity suppressing fiber can be spliced to the conventional transmission line. Therefore, optical power in the transmission line can be increased, and simultaneously, degradation in transmission due to the optical nonlinear effects can be suppressed by inserting this fiber immediately after the optical amplifier in which the optical nonlinear effects readily occur.

However, as described above, when WDM is employed to increase the transmission capacity, optical nonlinear effects called FWM take place because of presence of a plurality of wavelengths in the optical fiber, resulting in limitations on the bit rate and transmission distance.

The FWM is suppressed by varying chromatic dispersion of the optical fiber along the longitudinal direction. More specifically, when chromatic dispersion varies along the longitudinal direction of the optical fiber, phase velocity of light locally changes in the transmission line. For this reason, in WDM transmission, the phase matching condition between adjacent channels is disturbed, so FWM as a limitation factor on transmission can be suppressed.

Some methods are available to vary chromatic dispersion. For example, when a relative index difference α between the core and the third cladding is continuously changed along the longitudinal direction in the manufacture of the optical fiber, chromatic dispersion at 1.55 μm can be continuously varied.

Fig. 2 shows a change in chromatic dispersion at 1.55 μm when the relative index difference α between the core and third cladding of the optical fiber shown in Fig. 1 is changed. A relative index difference β between the first and third claddings is 1.5%.

The relative index difference α is given by:

$$\alpha = (n_0 - n_3)/n_0$$

The relative index difference β is given by:

$$\beta = (n_1 - n_3)/n_1$$

The optical fiber shown in Fig. 2, whose chromatic dispersion varies from +12 ps/nm/km to -12 ps/nm/km (chromatic dispersion variation: 24 ps/nm/km), is merely an example for explaining the chromatic dispersion variation obtained upon changing the relative index difference α from, e.g., 0% to -0.4%, so the chromatic dispersion value need not always be ±12 ps/nm/km.

Even when the relative index difference β between the first cladding and the third cladding is changed, chromatic dispersion at 1.55 μm can be continuously changed. Fig. 3 shows a change in chromatic dispersion at 1.55 μm observed upon changing the relative index difference β. The relative index difference α is -0.4%.

The chromatic dispersion can also be varied by changing the second cladding diameter along the longitudinal direction of the optical fiber. Fig. 4 shows a change in chromatic dispersion at 1.55 μm observed upon-changing the second cladding diameter. The relative index difference α is -0.4%, and the relative index difference β is 1.44%.

Figs. 5A to 5C show the relationships between the fiber length and chromatic dispersion obtained when the relative index differences α and β and the second cladding diameter are changed. In Fig. 5A, the wavelength is 1.55 μm, and the relative index difference β is 1.5%. In Fig. 5B, the wavelength is 1.55 μm, and the relative index difference α is -0.4%. In Fig. 5C, the wavelength is 1.55 μm, the relative index difference α is -0.4%, and the relative index difference β is 1.44%.

In all cases, chromatic dispersion continuously low-

ers as the fiber length increases, and the chromatic dispersion changes depending on the position in the optical fiber, as is apparent from Figs. 5A to 5C. Alternatively, the phase matching condition may be disturbed to suppress FWM by periodically changing both the relative index difference α between the core and third cladding and the relative index difference β between the first and third claddings along the longitudinal direction in the manufacture of the optical fiber.

The above-described optical nonlinearity suppressing fiber may be used in the following manner.

Fig. 6 shows the arrangement of the transmission line using the optical fiber shown in Fig. 1 and the relationship between the transmission distance and optical power level. As shown in Fig. 6, a transmitter 5 comprises a light source 5a and an optical amplifier 5b. A receiver 7 comprises a detector 7a and an optical amplifier 7b. An optical amplifier 6 is inserted between the transmitter 5 and the receiver 7. The transmitter 5 and the receiver 7 are connected through the optical amplifier 6, an optical nonlinearity suppressing fiber 8, and a conventional optical fiber 9.

This arrangement is based on the following reason. An actual optical fiber always has a transmission loss, optical power of an optical signal gradually becomes small during transmission. That is, the optical nonlinear effects are most conspicuous at positions (A and B in Fig. 6) immediately after optical amplifiers in the optical fiber transmission line. Therefore, when the optical nonlinearity suppressing fiber shown in Fig. 1 is inserted immediately after the optical amplifier in the conventional transmission line, the optical nonlinear effects can be effectively suppressed.

An optical fiber (to be referred to as an optical nonlinearity enhancing fiber hereinafter) which can be used for an optical switch or wavelength conversion device by inducing the optical nonlinear effects will be described next.

Fig. 7 shows the section of the optical nonlinearity enhancing fiber and its index distribution. As shown in Fig. 7, the refractive index n_0 of the core is made higher than the refractive index n_3 of the third cladding and lower than the refractive index n_1 of the first cladding to strengthen the light confinement effect at the center of the optical fiber, and the Aeff is reduced, thereby inducing the optical nonlinear effects (i.e., $n_1 > n_2 > n_3$, and $n_1 > n_0 > n_3$). With this arrangement, the intensity of light in the optical fiber becomes high. The optical nonlinear effects occur in accordance with the product of the intensity of light (power) and the nonlinear length, so this optical fiber can induce the optical nonlinear effects at a high efficiency.

Examples of the present invention will be described next.

Figs. 8A and 8B show a change in mode field diameter (to be referred to as an MFD hereinafter) when the relative index difference α between the core and the third cladding is changed.

The MFD is a parameter indicating the extension of field distribution of light in the fiber and is known to be proportional to the Aeff (Namihira et al., "Nonlinear Kerr Coefficient Measurements for Dispersion Shifted Fibers using Self-Phase Modulation Method at 1.55 μm", OEC '94).

As shown in Fig. 8A, when the absolute value of the relative index difference α is increased in the negative direction, the field distribution of light spreads to lower the intensity, so the optical fiber of this embodiment becomes the optical nonlinearity suppressing fiber for suppressing the optical nonlinear effects. From the viewpoint of manufacturing, the dose of fluorine which is doped to lower the refractive index of the core is limited, so the relative index difference α has its lower limit value within the range of -0.7% to -0.8% in fact.

On the other hand, as shown in Fig. 8B, when the relative index difference α is increased to the positive direction, the value of MFD becomes small. MFD of a general dual-shaped dispersion shifted fiber is effectively about 7.4 to 8.4 μm (Aeff = 41 to 53 μm^2). With the relative index difference *a* having a positive value, the field distribution becomes narrower than that of the DSF, and the intensity of light rises, so the optical nonlinearity enhancing fiber is obtained.

If the electric field has a Gaussian distribution, Aeff $= \pi \times (MFD/2)^2$ is obtained. When MFD increases, the Aeff also increases. However, if the optical fiber of the present invention is formed as the optical nonlinearity suppressing fiber (i.e., $\alpha < 0$), the field distribution deviates from the Gaussian distribution, so the right-hand side of the above equation must be multiplied by a correction coefficient c ($c > 1$).

Fig. 9 shows a change in MFD observed when the ratio of the core diameter to the first cladding diameter is changed. In Fig. 9, a bullet indicates a value when the relative index difference α between the core and third cladding is 0%; and a hollow bullet, a value when the relative index difference α is +0.3%. As shown in Fig. 9, when the relative index difference *a* is 0%, and the ratio of the core diameter to the first cladding diameter is 0.4 or less, MFD becomes smaller than that of the DSF. Since the intensity of light rises, the optical nonlinearity enhancing fiber is obtained. When the relative index difference α is +0.3%, and the ratio of the core diameter to the first cladding diameter is 0.5 or less, the optical nonlinearity enhancing fiber is expected to be obtained.

The FWM suppressing effect will be described next.

Fig. 10 shows the FWM suppressing effect. As is apparent from Fig. 10, FWM can be suppressed by changing chromatic dispersion along the longitudinal direction of the optical fiber.

Fig. 10 shows the dependence of the FWM generation efficiency (normalized by defining the generation efficiency for a dispersion variation of 0 as 1) in a chromatic-dispersion varying fiber (length: 40 km), whose chromatic dispersion linearly increases along the longitudinal direction of the optical fiber, on the chromatic dis-

persion variation (chromatic dispersion difference between the input side and output side) (Fig. 11).

When the chromatic dispersion variation is 4 ps/nm/km, the FWM generation efficiency is 1/10 that of the normal optical fiber whose chromatic dispersion variation is 0, or less, so a sufficient suppressing effect can be obtained. The suppressing effect can be increased by increasing the chromatic dispersion variation. In addition, as is apparent from Fig. 10, the FWM generation efficiency can be suppressed to about 0.03 with a chromatic dispersion variation of 20 ps/nm/km. For a chromatic dispersion variation of 24 ps/nm/km, a larger FWM suppressing effect is expected.

Fig. 12 shows the relationship between the core diameter for satisfying the single-mode condition and the relative index difference β between the first and third claddings when the relative index difference α between the core and the third cladding is changed. The hatched portion in Fig. 12 indicates a region where the single-mode condition cannot be satisfied at 1.55 μm. As the relative index difference α becomes small, the number of combinations of the core diameter and relative index difference β for satisfying the single-mode condition increases.

In an optical fiber shown in Fig. 13, the Aeff could be increased to about 150 μm^2 at a zero-dispersion wavelength of 1.55 μm by setting the relative index difference α at about -0.3% and relative index difference β at about 1%. Fig. 14 shows a change in zero-dispersion wavelength when each relative index difference is changed while maintaining the index relationships $n_1 > n_2 > n_3$ and $n_1 > n_0$. As is apparent from Fig. 14, zero dispersion in the wavelength band of 1.4 to 1.5 μm is realized. By changing the combination of relative index differences, zero dispersion in the wavelength band of 1.3 to 1.6 μm or in a longer wavelength band can also be realized.

Considering the handling characteristics of the above-described optical fiber in actual use for a transmission line or the like, the optical fiber must have a small bending loss. The optical fiber of this embodiment could improve its bending loss characteristics by increasing the relative index difference β. Fig. 15 shows the bending loss characteristics with respect to the bending radius of the optical fiber of this embodiment. As is apparent from Fig. 15, the bending loss decreases as the relative index difference β increases. In addition, the optical fiber of this embodiment can obtain almost the same bending loss characteristics as those of the conventional DSF (about several dB/m for a bending radius of 1 cm; Aeff is about 50 μm^2) by setting the relative index difference β at about 1.5%. In this case, the Aeff is about 120 μm^2.

According to the optical fiber of the present invention, even when the zero-dispersion wavelength is designed in a band of 1.55 μm, the field distribution does not concentrate to the center of the optical fiber. For this reason, the Aeff can be made larger than that of the conventional DSF by twice or more while maintaining almost the same bending loss characteristics. More specifically, the intensity of light lowers to suppress the optical nonlinear effects, and consequently, degradation in signal waveform is suppressed, so the bit rate and transmission distance can be increased.

In addition, when the phase matching condition between wavelengths is disturbed by changing the zero-dispersion wavelength in a band of 1.55 μm along the longitudinal direction of the optical fiber, the FWM generation efficiency can be lowered. Therefore, the wavelength interval in WDM can be reduced to increase the number of channels.

On the other hand, when the Aeff is decreased, the intensity of light in the optical fiber can be made high. Since the optical nonlinear effects can be efficiently generated, an optical fiber suitable for an optical switch or wavelength conversion device can be provided.

Claims

1. An optical fiber characterized by comprising:

   a core (1) having a refractive index n_0;
   a first cladding (2) formed around said core and having a refractive index n_1;
   a second cladding (3) formed around said first cladding and having a refractive index n_2; and
   a third cladding (4) formed around said second cladding and having a refractive index n_3,
   wherein the refractive indices have relationships $n_1 > n_2 > n_3$ and $n_1 > n_0$.

2. A fiber according to claim 1, wherein the refractive indices further have a relationship $n_3 \geq n_0$.

3. A fiber according to claim 1, wherein the refractive indices further have a relationship $n_0 > n_3$.

4. A fiber according to claim 2, wherein a relative index difference α between said core and said third cladding continuously changes along a longitudinal direction of said optical fiber.

5. A fiber according to claim 3, wherein a relative index difference α between said core and said third cladding continuously changes along a longitudinal direction of said optical fiber.

6. A fiber according to claim 2, wherein a relative index difference β between said first cladding and said third cladding continuously changes along a longitudinal direction of said optical fiber.

7. A fiber according to claim 3, wherein a relative index difference β between said first cladding and said third cladding continuously changes along a longi-

tudinal direction of said optical fiber.

8. A fiber according to claim 2, wherein a diameter of said second cladding continuously changes along a longitudinal direction of said optical fiber.

9. A fiber according to claim 3, wherein a diameter of said second cladding continuously changes along a longitudinal direction of said optical fiber.

10. A fiber according to claim 4, wherein the relative index difference α between said core and said third cladding monotonically increases or monotonically decreases along the longitudinal direction of said optical fiber.

11. A fiber according to claim 5, wherein the relative index difference α between said core and said third cladding monotonically increases or monotonically decreases along the longitudinal direction of said optical fiber.

12. A fiber according to claim 6, wherein the relative index difference β between said first cladding and said third cladding monotonically increases or monotonically decreases along the longitudinal direction of said optical fiber.

13. A fiber according to claim 7, wherein the relative index difference β between said first cladding and said third cladding monotonically increases or monotonically decreases along the longitudinal direction of said optical fiber.

14. A fiber according to claim 8, wherein the diameter of said second cladding monotonically increases along the longitudinal direction of said optical fiber.

15. A fiber according to claim 8, wherein the diameter of said second cladding monotonically decreases along the longitudinal direction of said optical fiber.

16. A fiber according to claim 9, wherein the diameter of said second cladding monotonically increases along the longitudinal direction of said optical fiber.

17. A fiber according to claim 9, wherein the diameter of said second cladding monotonically decreases along the longitudinal direction of said optical fiber.

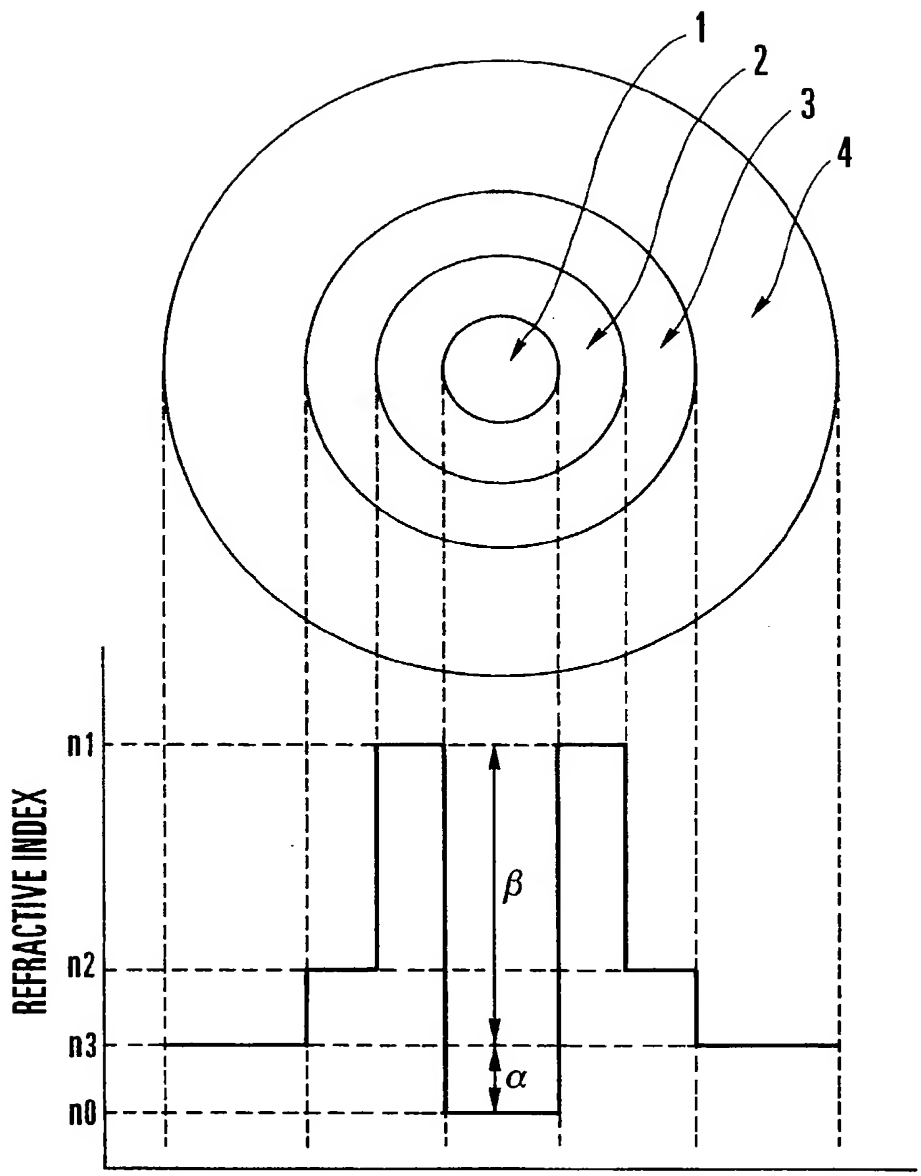


FIG. 1

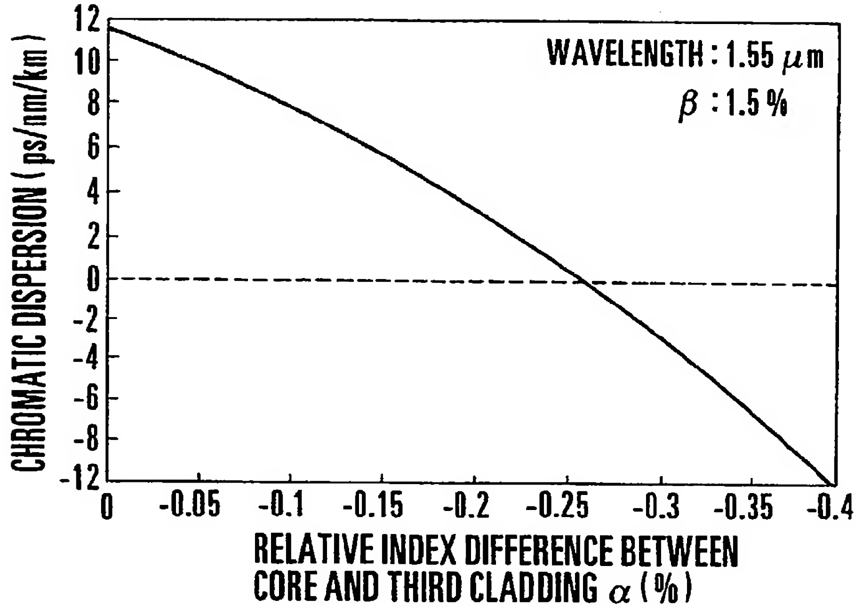

WAVELENGTH : 1.55 μm
β : 1.5 %
CHROMATIC DISPERSION (ps/nm/km)
12
10
8
6
4
2
0
-2
-4
-6
-8
-12
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
-0.4
RELATIVE INDEX DIFFERENCE BETWEEN
CORE AND THIRD CLADDING α (%)

FIG. 2

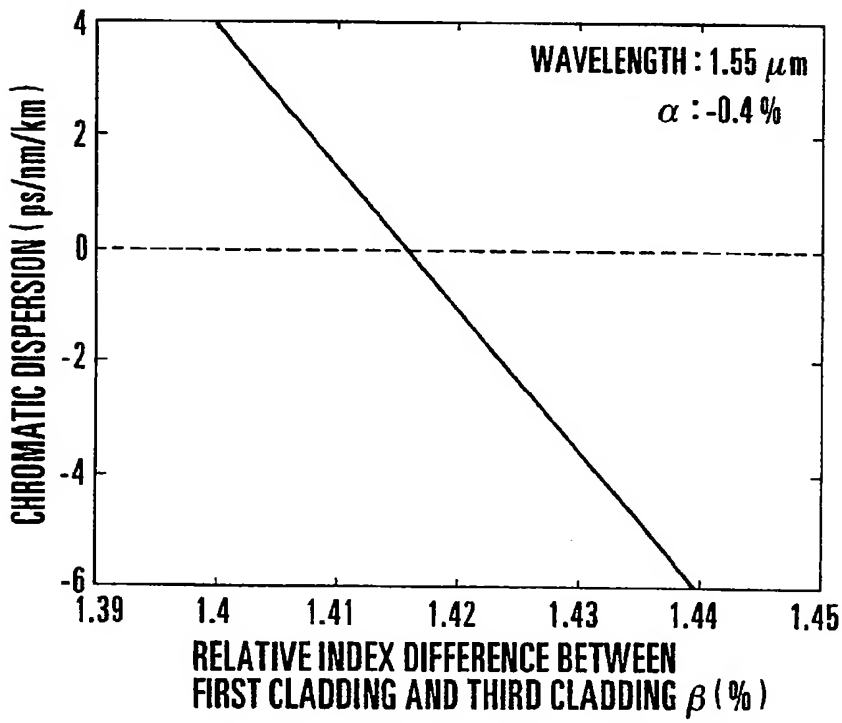
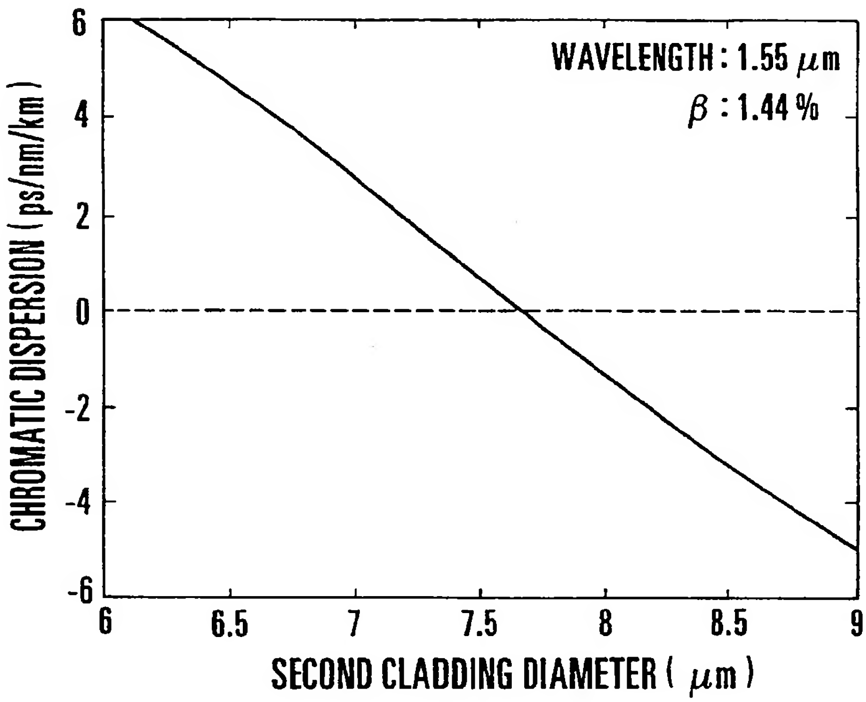

WAVELENGTH : 1.55 μm
α : -0.4 %
CHROMATIC DISPERSION (ps/nm/km)
4
2
0
-2
-4
-6
1.39
1.4
1.41
1.42
1.43
1.44
1.45
RELATIVE INDEX DIFFERENCE BETWEEN
FIRST CLADDING AND THIRD CLADDING β (%)

FIG. 3


WAVELENGTH : 1.55 μm
β : 1.44 %
CHROMATIC DISPERSION (ps/nm/km)
6
4
2
0
-2
-4
-6
6
6.5
7
7.5
8
8.5
9
SECOND CLADDING DIAMETER (μm)

F I G. 4

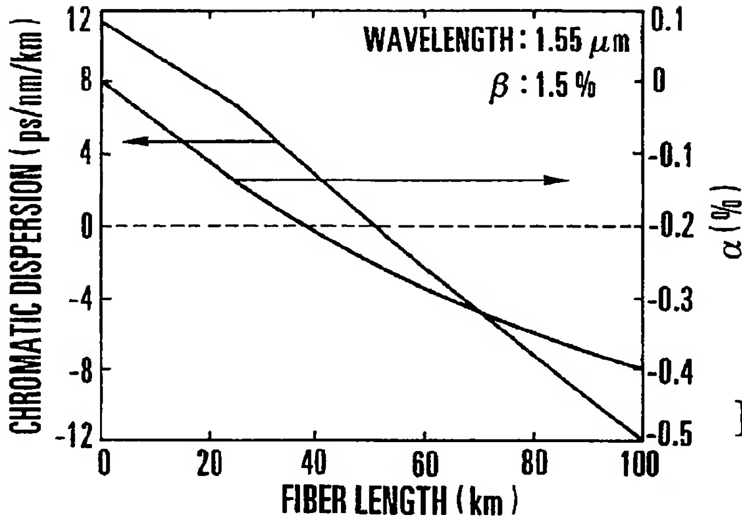


FIG.5A

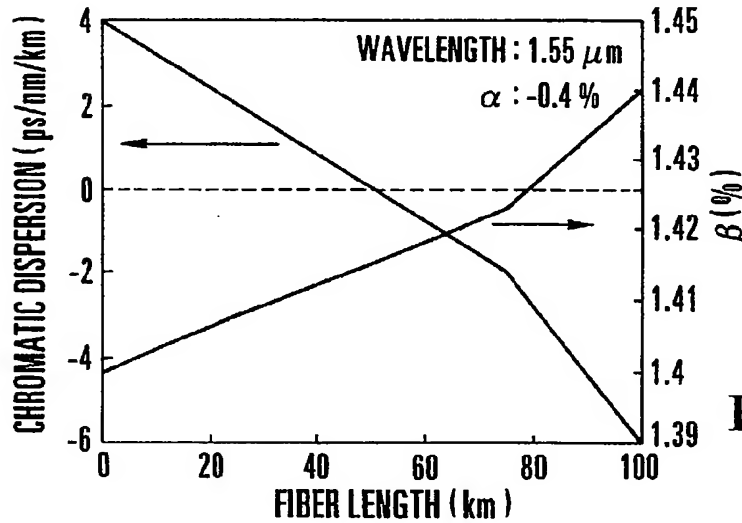


FIG.5B

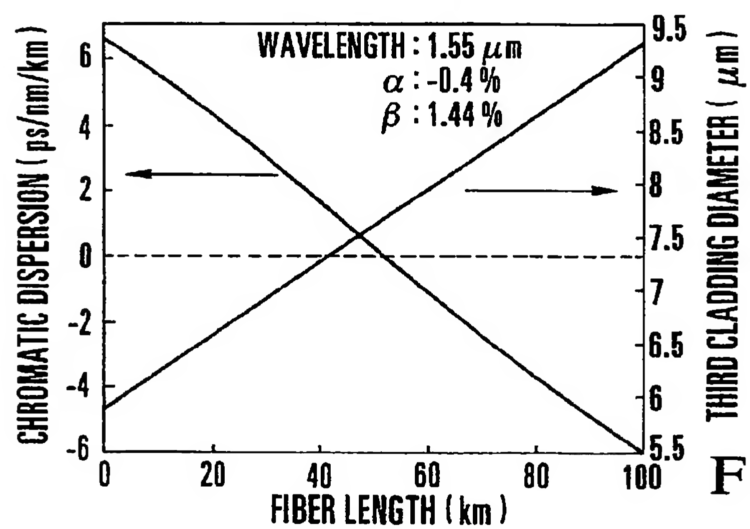
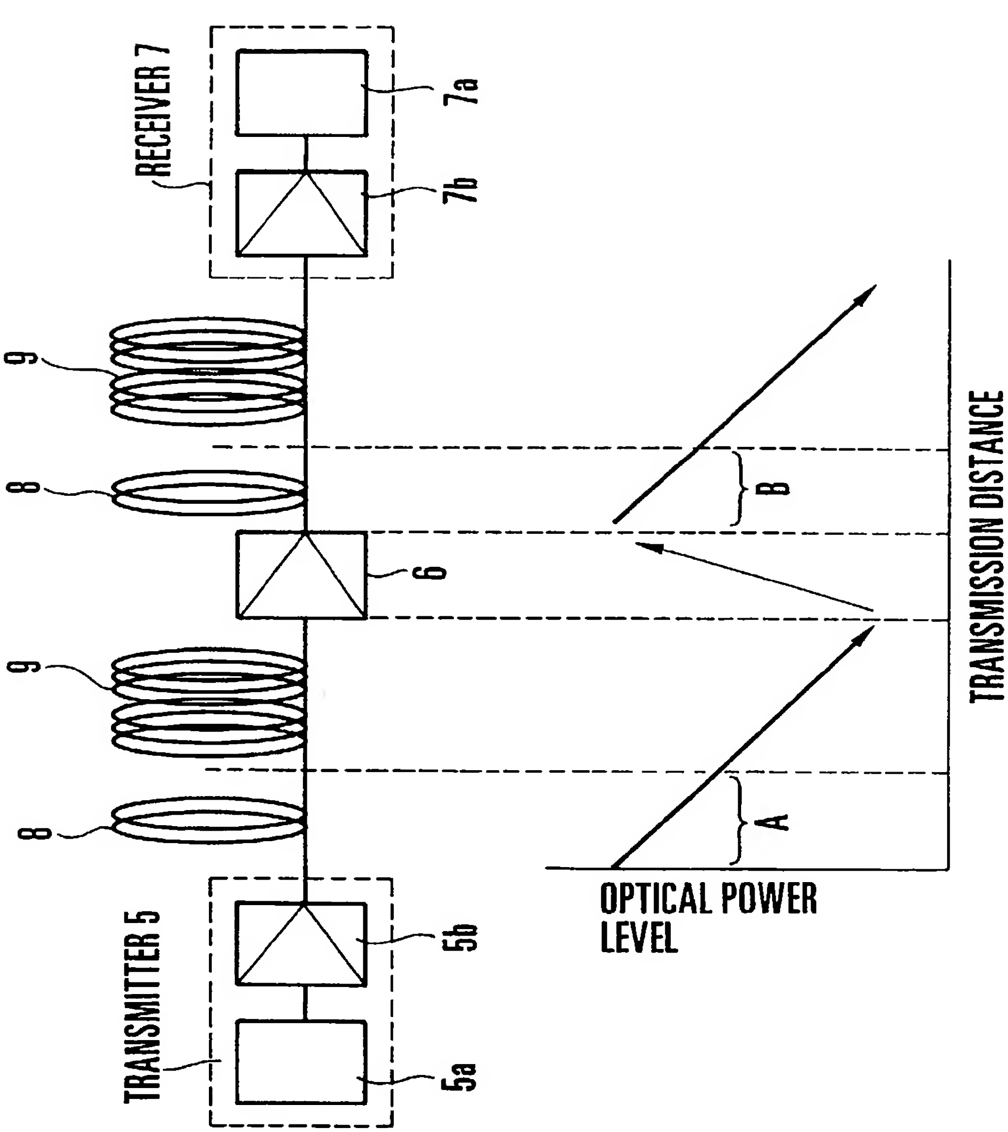


FIG.5C


TRANSMITTER 5
5a
5b
8
9
6
8
9
RECEIVER 7
7b
7a
A
B
OPTICAL POWER LEVEL
TRANSMISSION DISTANCE

F I G. 6

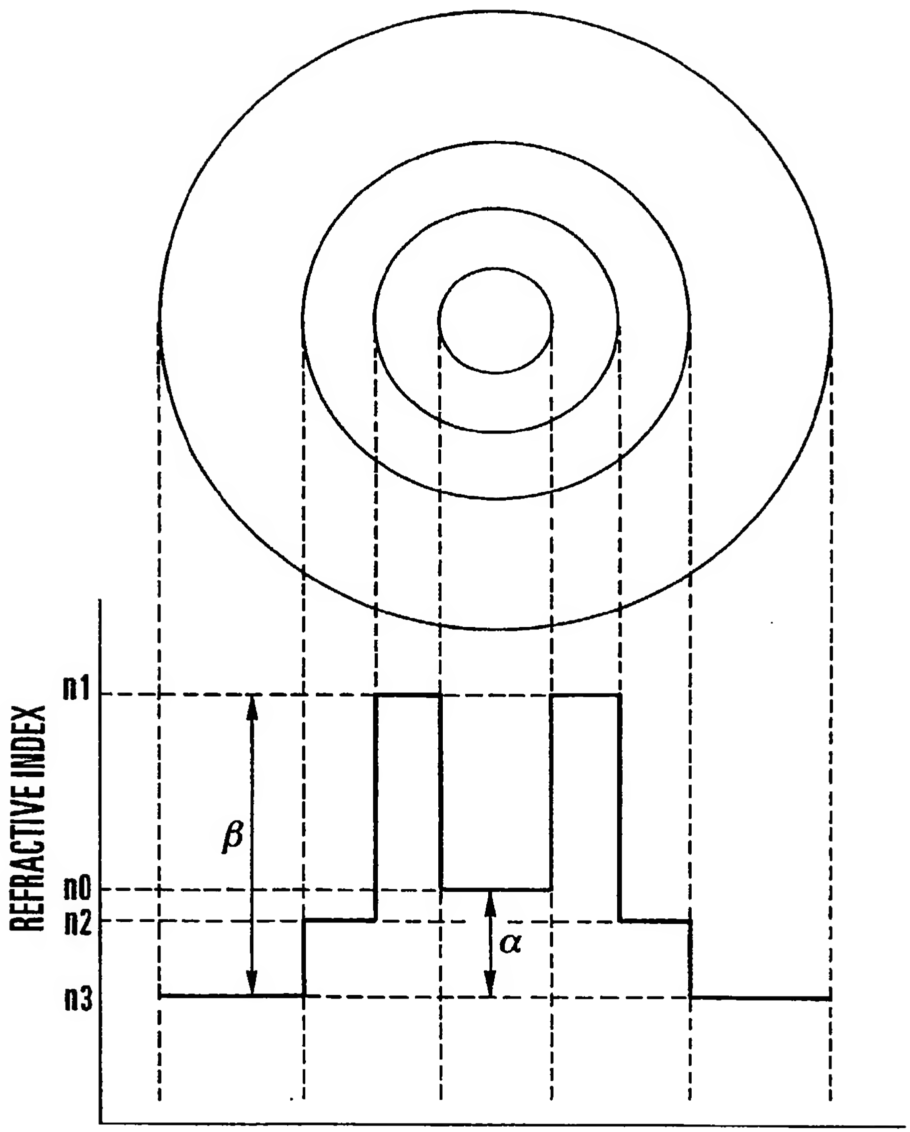


FIG.7

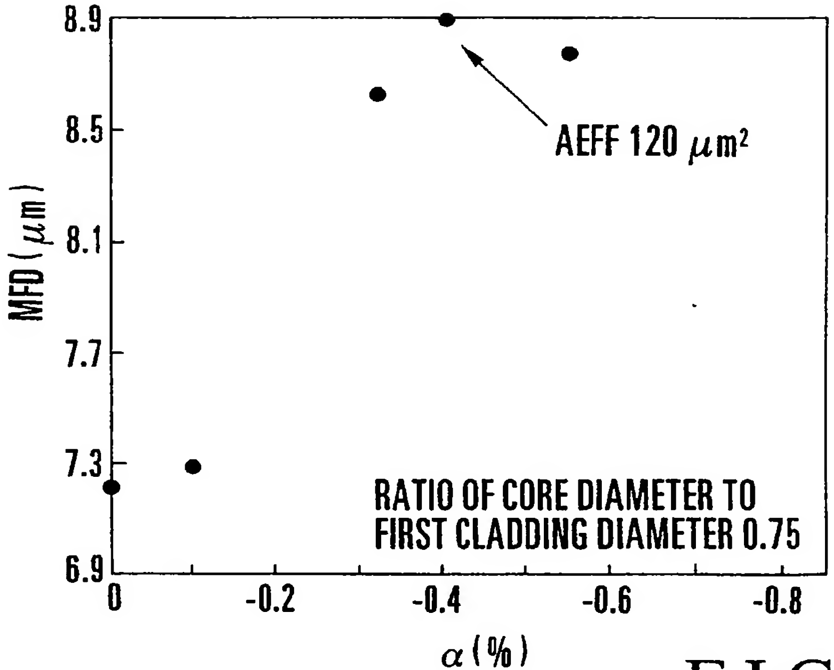

8.9
8.5
8.1
7.7
7.3
6.9
MFD (μm)
AEFF 120 μm²
RATIO OF CORE DIAMETER TO
FIRST CLADDING DIAMETER 0.75
0
-0.2
-0.4
-0.6
-0.8
α (%)

FIG.8A

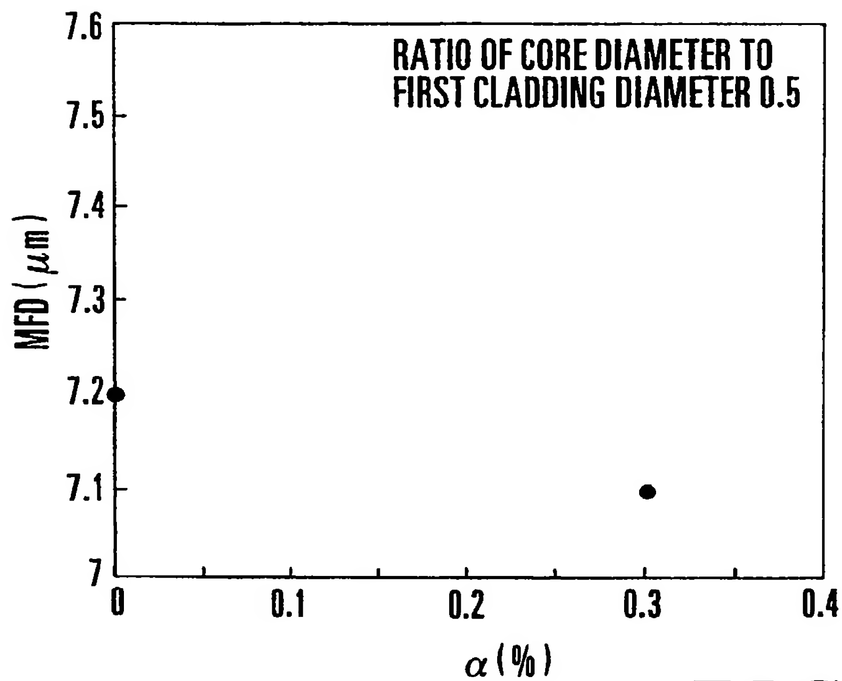

7.6
7.5
7.4
7.3
7.2
7.1
7
MFD (μm)
RATIO OF CORE DIAMETER TO
FIRST CLADDING DIAMETER 0.5
0
0.1
0.2
0.3
0.4
α (%)

FIG.8B

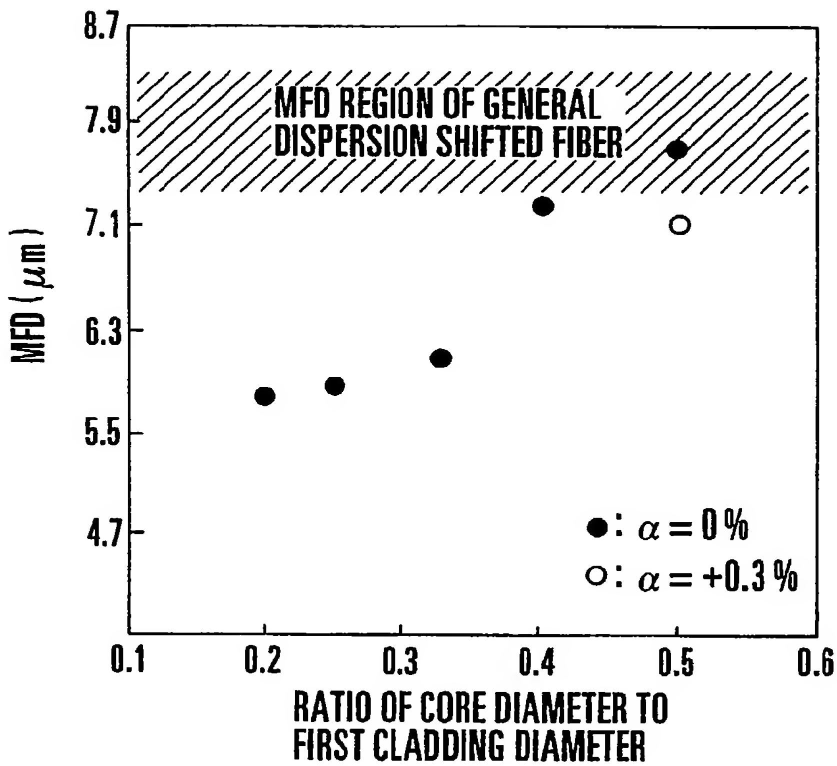
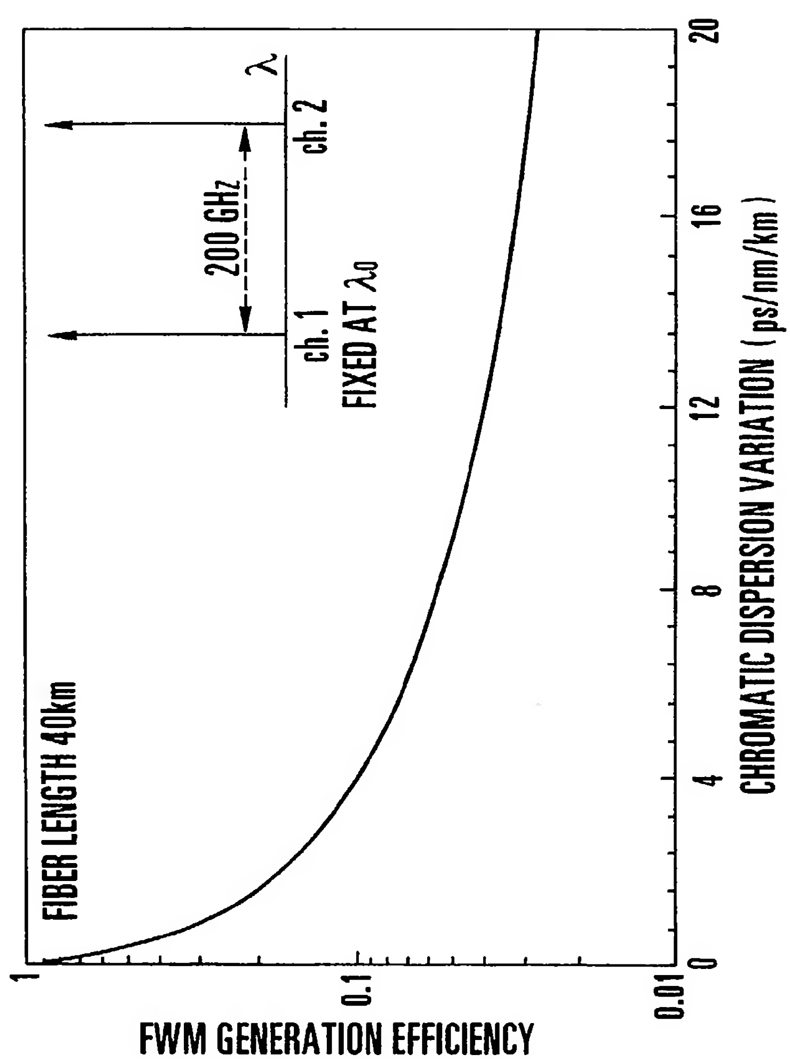
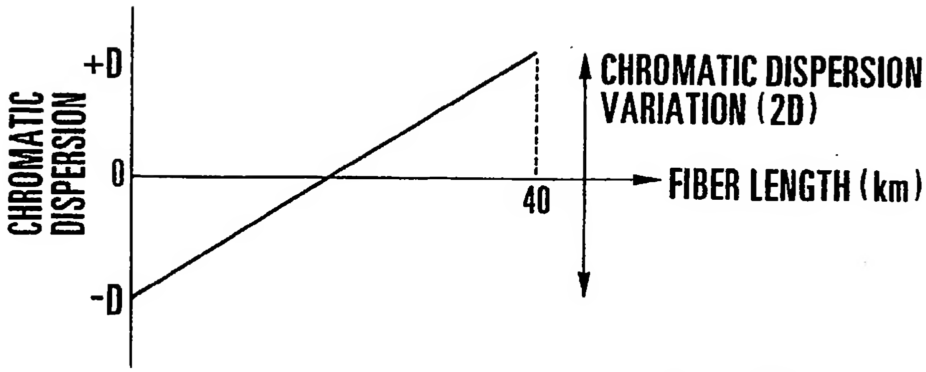

8.7
7.9
7.1
6.3
5.5
4.7
MFD (μm)
MFD REGION OF GENERAL
DISPERSION SHIFTED FIBER
●: α = 0 %
○: α = +0.3 %
0.1
0.2
0.3
0.4
0.5
0.6
RATIO OF CORE DIAMETER TO
FIRST CLADDING DIAMETER

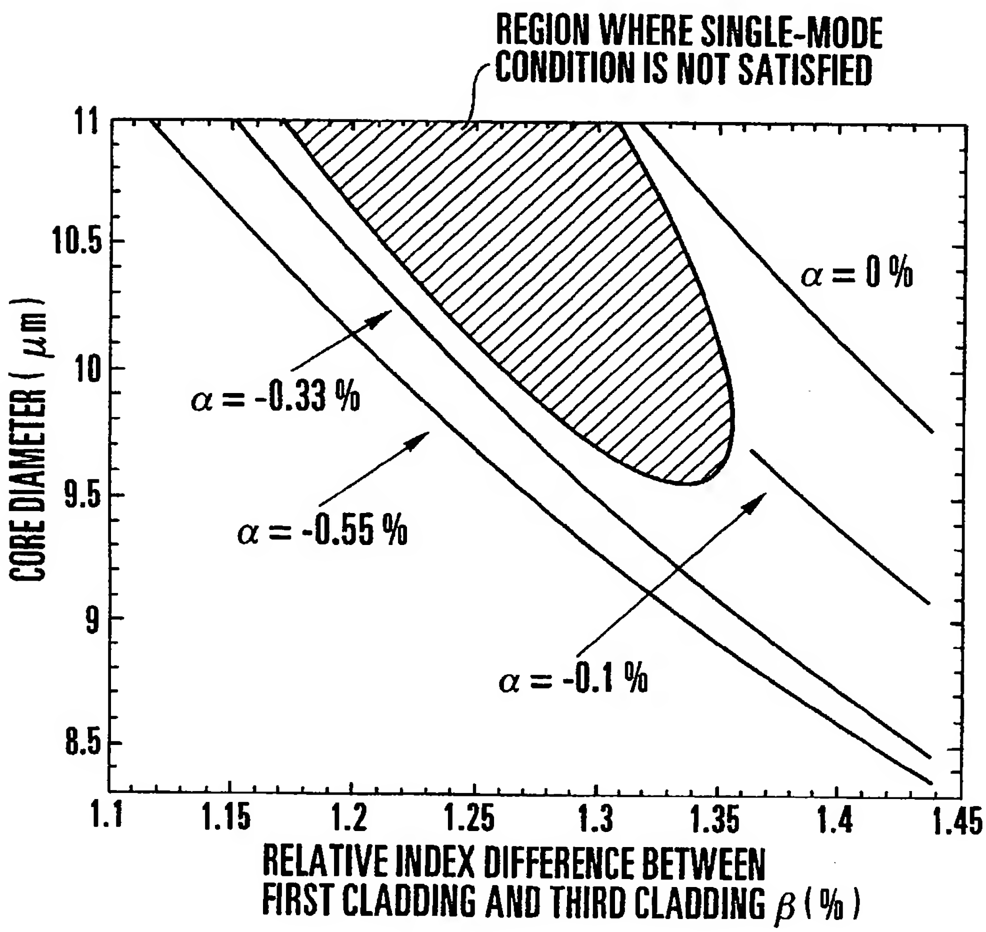
FIG. 9


FWM GENERATION EFFICIENCY
1
0.1
0.01
FIBER LENGTH 40km
200 GHz
λ
ch. 1
ch. 2
FIXED AT λ_0
0
4
8
12
16
20
CHROMATIC DISPERSION VARIATION (ps/nm/km)

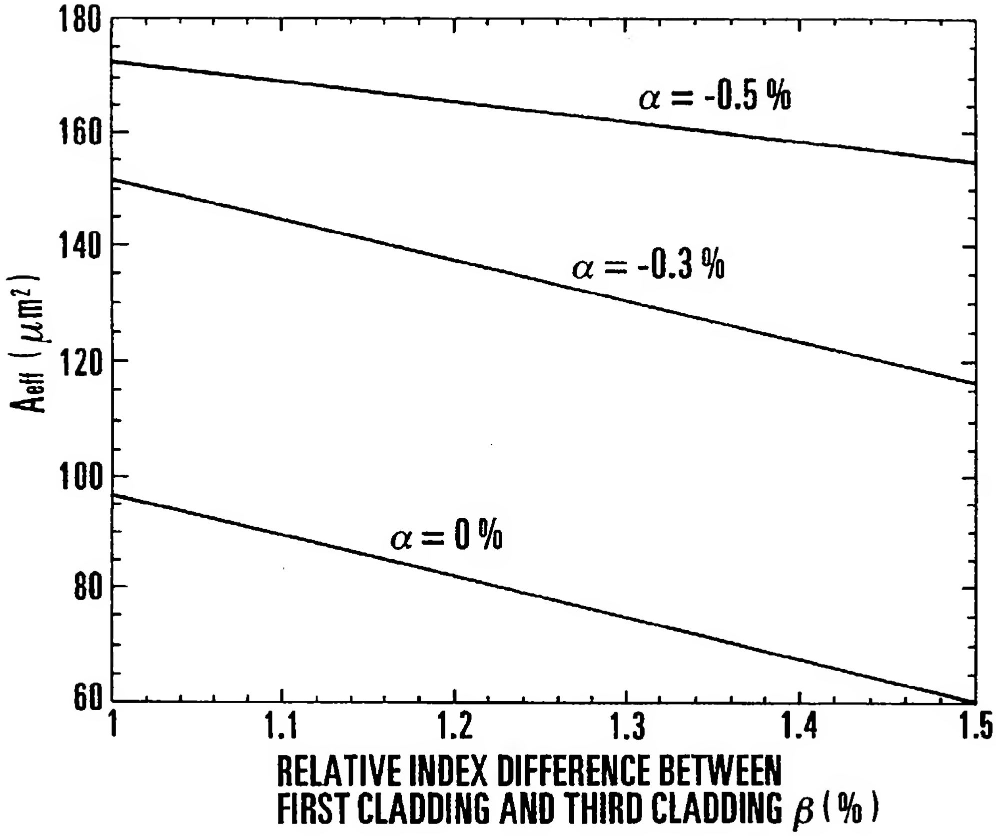
F I G. 10


CHROMATIC DISPERSION
+D
0
-D
40
CHROMATIC DISPERSION VARIATION (2D)
FIBER LENGTH (km)

F I G. 11


REGION WHERE SINGLE-MODE CONDITION IS NOT SATISFIED
11
10.5
10
9.5
9
8.5
CORE DIAMETER (μm)
α = 0 %
α = -0.33 %
α = -0.55 %
α = -0.1 %
1.1
1.15
1.2
1.25
1.3
1.35
1.4
1.45
RELATIVE INDEX DIFFERENCE BETWEEN FIRST CLADDING AND THIRD CLADDING β (%)

F I G. 12



180
160
140
120
100
80
60
1
1.1
1.2
1.3
1.4
1.5
A_{eff} (μm^2)
α = -0.5 %
α = -0.3 %
α = 0 %
RELATIVE INDEX DIFFERENCE BETWEEN
FIRST CLADDING AND THIRD CLADDING β (%)

F I G. 13

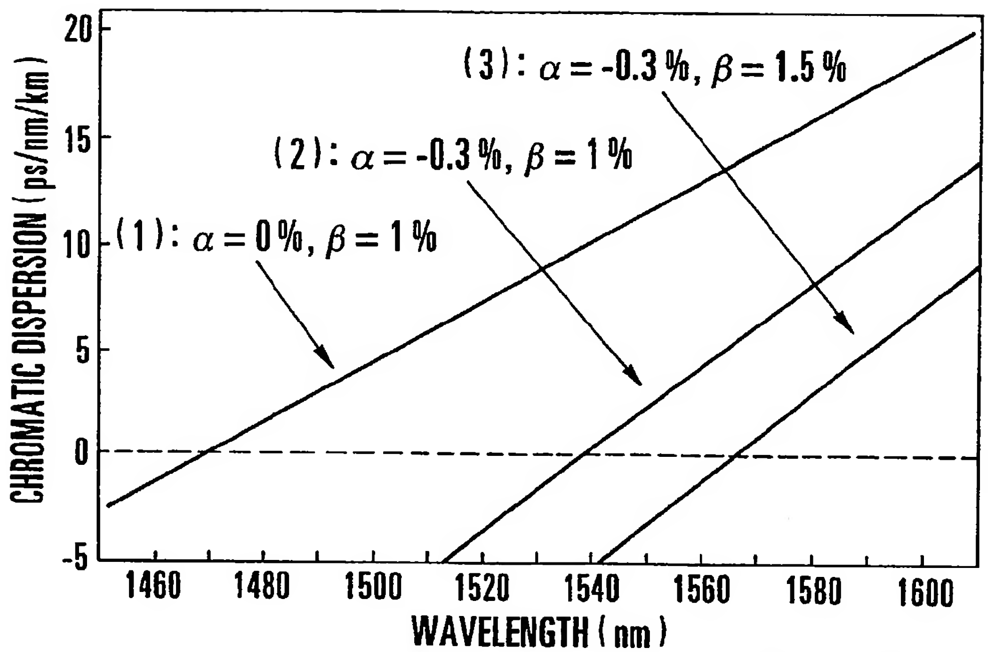

CHROMATIC DISPERSION (ps/nm/km)
20
15
10
5
0
-5
1460
1480
1500
1520
1540
1560
1580
1600
WAVELENGTH (nm)
(1): $\alpha = 0\%$, $\beta = 1\%$
(2): $\alpha = -0.3\%$, $\beta = 1\%$
(3): $\alpha = -0.3\%$, $\beta = 1.5\%$

FIG. 14

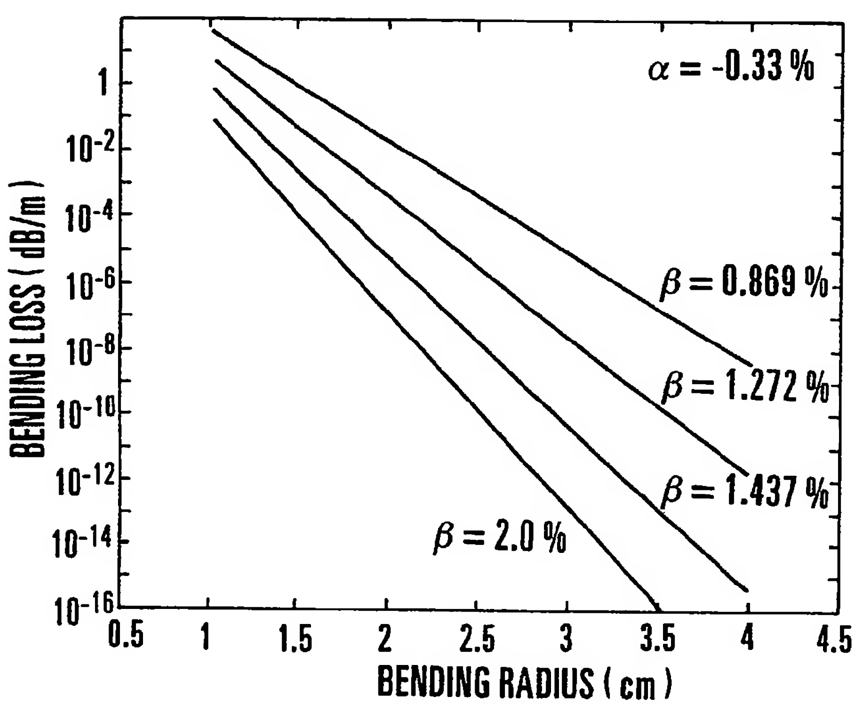

BENDING LOSS (dB/m)
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
0.5
1
1.5
2
2.5
3
3.5
4
4.5
BENDING RADIUS (cm)
$\alpha = -0.33\%$
$\beta = 0.869\%$
$\beta = 1.272\%$
$\beta = 1.437\%$
$\beta = 2.0\%$

FIG. 15

zero magnitude at its outer radius to eliminate radiation or absorption by a covering material and (2) very low losses. With prior art compositions, it was difficult to deposit sufficient silica for adequate clad thickness because the substrate tube in which the deposition occurred collapsed at the high deposition temperatures needed. The problems associated with silica clads can not be eliminated, at the present time, by using commercially available silica tubing because the impurities in such tubing cause prohibitively high loss clads.

SUMMARY OF THE INVENTION

A single mode glass transmission line for electromagnetic energy having a wavelength between 0.5μm and 2.0μm. The core is surrounded by a clad which has a refractive index smaller than that of the core. Both core and clad consist essentially of the same type of multicomponent glass composition and the relative concentrations of the components in the core and clad permit only single mode propagation. The components are selected from the group consisting of P_2O_5, B_2O_3, Al_2O_3, GeO_2 and SiO_2. As an example, the core and clad consist essentially of a borosilicate composition with the ratio of SiO_2/B_2O_3 concentrations in both core and clad being within the range from 3:1 to 30:1. The ratio in the core exceeds the ratio in the clad by an amount such that the difference between the refractive indices of core and clad is less than approximately $3\lambda^2/(4\pi^2a^2n^2)$ where λ is the wavelength, a is the core radius and n is the index of refraction of the core.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a perspective view of a section of a glass transmission line;

FIG. 2 is a plot of the single mode condition for $\lambda = 0.9\mu$m and $V = 2.40$ in terms of $\Delta n/n$ versus core radius;

FIG. 3 is a plot showing the decrease in refractive index as the mole percent of B_2O_3 in the fiber increases; and

FIG. 4 is a plot of energy loss in db/km versus wavelength for a typical fiber of this invention.

DETAILED DESCRIPTION

It has not hitherto been realized that single mode fibers could be fabricated with both core and clad consisting essentially of the same type of multicomponent glass composition and the refractive index difference between core and clad obtained by varying the relative concentrations of the components, selected from the group consisting of P_2O_5, GeO_2, Al_2O_3, B_2O_3 and SiO_2, of the glass composition. As an example, a single mode fiber is fabricated with both core and clad consisting of a borosilicate glass and the required index difference between core and clad obtained by varying the ratios of SiO_2/B_2O_3 concentrations in the core and clad. These compositions permit accurate control of the composition of the core and clad and because of the relatively high boron content in the clad, deposition of sufficient clad thickness is easy because of the low deposition temperature. Preforms, from which the fibers are drawn, with these compositions are easier to collapse and the drawn fibers have no drawing induced absorption near 0.63μm such as described in *Journal of the Optical Society of America* 64 pp. 475–481, April 1974.

FIG. 1 is a perspective view of an optical transmission line **1**, i.e., an optical fiber, of this invention having a core **2** and a clad **3**. Both core **2** and clad **3** consist

essentially of the same type of glass composition, e.g., B_2O_3 modified SiO_2, i.e., a borosilicate glass. Not shown are the means for injecting light into the fiber and means for extracting and detecting light from the fiber. Since it is generally anticipated that a plurality of fibers will be used, the fiber may be covered with additional layers (not shown), e.g., of a highly absorbent material to prevent crosstalk between adjacent fibers or with another glassy layer from the fabrication method.

Although, in general, exact solutions for the electromagnetic field within an optical fiber cannot be obtained, for the very practical case of a fiber having a circular cross section and a difference between the refractive indices of core and clad much less than one, approximate solutions can be obtained. From these solutions, it is determined that the single mode condition $V = Ka\sqrt{2N\Delta n} < 2.405$, where $K = 2\pi/\lambda$, a is the core radius, n is the refractive index of the core and Δn is the difference between the refractive indices of the core and clad, must be satisified if there is to be single mode propagation within a fiber. Theoretically, there is no mimimum V value and there will be single mode propagation for even the lowest frequencies, provided the wavelength does not exceed the core radius, and largest core radii. There are two reasons for making fibers with V as close to 2.405 as possible. First, as V decreases, more and more of the electromagnetic field energy is within the clad and effective guidance becomes more difficult as the energy within the clad tends to escape from the fiber. Second, because fiber splicing becomes more difficult as the core radius decreases, it is desirable to make the core as large as practicable, i.e., have V as close to 2.405 as possible. FIG. **2** plots, for $V = 2.4$ and $\lambda = 0.9\mu$m, the single mode condition with parameters of $\Delta n/n$ and core radius in μms. All fibers having both $\Delta n/n$ and a values below the curve are single mode fibers for $\lambda = 0.9\mu$m. The curve will shift upward or downward, in an easily ascertainable manner, as λ becomes longer or shorter, respectively.

Several important design considerations for fibers are apparent from FIG. 2. Large radii cores, which are desirable to alleviate splicing problems, require fibers with smaller values of $\Delta n/n$, which for radii as large as those of typical multimode fibers, have high losses because any real fiber has small deviations from linearity (microbends) in which electromagnetic energy penetrates further into the clad than it would have otherwise and is lost from the fiber. This places a lower limit on Δn of about 10^{-4}. Further, real fibers have small and periodic perturbations which cause energy to be transferred from one mode to another mode. In a single mode fiber such a mode conversion transfers energy to a mode that is not propagated and is lost. As the core radius increases, the period of the perturbations causing mode conversion both increases and becomes more probable. The resulting mode conversion increases loss and imposes a practical upper limit on core radius of approximately 12μm. The minimum core radius is dictated by two considerations. First, there is the previously mentioned and very real practical problem associated with the necessity for accurately aligning fibers with small cores for splicing to other fibers or connecting to light sources or detectors to prevent energy losses from becoming prohibitively large. Second, there is a fundamental problem of large scattering losses from stimulated Brillouin or Raman scattering when the guided electromagnetic energy exceeds a threshold power density level which is approximately two orders

of magnitude higher for Raman than for Brillouin scattering. Below the threshold, there is no scattering loss but above the threshold, the electromagnetic energy is shifted in frequency and lost. From these considerations, a practical lower limit on core radius is approximately 3μm.

There is an additional design consideration for fibers with small Δn values. In these weakly guiding fibers, the electromagnetic field extends a significant distance into the clad. As a consequence, unless the clad is sufficiently thick so that the magnitude of the radially decreasing electromagnetic field is essentially zero at the outer radius of the clad there will be significant losses. If the electromagnetic field magnitude is non-zero at the outer radius, energy will be lost either through radiation or interaction with an absorbing layer convering the fiber. This type of loss is also responsible for microbending losses. A useful minimum radius for the clad is approximately six times that of the core radius.

The refractive indices of the core and clad are determined by the ratio of the SiO_2/B_2O_3 concentrations in core and clad. As the B_2O_3 concentration increases, i.e., as the ratio of the SiO_2/B_2O_3 concentration decreases the refractive index increases as shown in FIG. 3 which plots the decrease, from the value for pure silica, in refractive index of the fiber, as measured after fiber drawing, as the mole percent of B_2O_3 increases. These measurements were made near 0.54μm and are fairly representative of the visible and infrared indices. The extremely refractory nature of compositions with high silica content makes 30:1 the highest practical SiO_2/B_2O_3 ratio. The susceptibility to water attack of compositions with high B_2O_3 concentrations makes the lowest practical ratio approximately 3:1. The preferred range is between 4:1 and 20:1. The necessary change in composition between core and clad is determined by considering the desired core radius, the wavelength of the light transmitted in the fiber and the desire to have V close to 2.405. These considerations determine Δn when the refractive index of core or clad is known. As can be seen from FIG. 3, which plots the decrease, as measured in drawn fibers, in refractive index from the value of pure silica as the mole percent concentration of B_2O_3 increases, a considerable number of small compositional variations between core and clad yield values of Δn that satisfy the single mode condition. The small compositional difference between core and clad resulting from the small value of Δn ensures that core and clad have similar thermal expansion properties and alleviates difficulties often encountered in fiber fabrication when the fiber undergoes a rapid and substantial temperature change such as encountered in the fiber drawing process.

The fibers of this invention may conveniently be fabricated by the modified chemical vapor deposition (MCVD) technique. A thin walled hollow fused quartz tube is supported at both ends and rotated in a glass working lathe. A heat source, e.g., an oxy-hydrogen burner, periodically traverses the length of the tube. A gas stream containing controlled amounts of silicon tetrachloride ($SiCl_4$), boron trichloride (BCl_3) and oxygen flows through the tube. Reactions occur both at the inner surface of the tube and in the homogeneous gas stream. The former results in a glassy deposit in the heated zone of the glass tube produced by the heat source and the latter produces particles which settle on the inner surface of the tube downstream from the heated zone and are fused to a clear film as the heat source traverses the tube. In this manner, uniform depositions, which ultimately form the core and clad of the fiber, are made along the length of the tube. Typically, the heat source traverse the length of the tube 75 times with the relative concentrations and flow rates of silicon tetrachloride, boron trichloride and oxygen being adjusted, if necessary, after each traversal to obtain the desired change in refractive index between or within core and clad. Unlike optimum multimode fibers, single mode fibers need no radial variation in refractive index in either core or clad, i.e., they may be step index or approximately step index fibers. Typical deposition temperatures are within the ranges of 1450°–1550° C for the clad and 1550°–1650° C for the core with the precise temperatures actually chosen depending upon the composition of the core and clad.

After deposition has been completed, the fused quartz tube with glassy deposits, usually referred to as a preform, is collapsed with a slight positive pressure in the hollow section of the preform to maintain a circular cross section and the deposits form a solid mass. The preform is attached to a feed mechanism that maintains the preform tip accurately positioned with respect to a heat source that softens the tip. After the tip softens and forms a taper, a fiber is drawn from the taper and attached to a drum which both rotates and translates and thus winds a layer of the fiber on the drum. The fiber diameter is controlled by the preform size, the rate of preform feed, the drawing temperature, and the peripheral velocity of the drum in well known manner. In general, the drawing process maintains the ratio between the core and clad radii in the fiber equal to the ratio of the radii of the core and clad deposits in the preform.

Example: The B_2O_3 concentrations in the core and clad were 9.1 and 14.2 mole percent, respectively, with the remaining material being SiO_2. Δn was 0.0017. The core radius was 4.5μm and the clad radius was 8 times greater. ν was less than 2.4 for wavelengths greater than 0.85μm. The loss in electromagnetic energy, in db/km, as a function of wavelength is shown in FIG. 4. The loss decreases generally as expected from the $1/\lambda^4$ dependence of Rayleigh scattering. The increase in loss between 0.9μm and 1.0μm is due to the presence of OH radicals.

For some fibers, ν may exceed 2.405 by a small amount, i.e., ν may be as large as about 4.0, and although the higher ν value theoretically allows modes of order higher than the first to propagate, for practical purposes, these fibers are also single mode fibers because all modes, on other than the lowest order, are rapidly lost from the clad through radiation or absorption by material coating the clad, e.g., another glassy layer.

What is claimed is:

1. A single mode glass transmission line for electromagnetic energy having a wavelength between 0.5μm and 2.0μm, said line consisting essentially of a core having a first refractive index, said core having a radius less than 12μm, and a clad having a second refractive index, said clad surrounding said core, said first refractive index exceeding said second refractive index; characterized in that said core and said clad consist essentially of SiO_2 and B_2O_3, the ratios of SiO_2/B_2O_3 concentrations within said core and said clad being within the range between 3:1 and 30:1, said ratio in said core exceeding said ratio in said clad by an amount such that the difference between said first refractive index and said second refractive index is less than approximately

$(2.4\lambda)^2/(8\pi^2a^2n)$ where λ is said wavelength, a is said radius and n is said first refractive index.

2. Transmission line as recited in claim **1** in which said ratios are within the range from 4:1 and 20:1.

3. Transmission line as recited in claim **1** in which said core has a radius between 3.0μ and 12.0μm.

4. Transmission line as recited in claim **3** in which said clad has a radius at least seven times greater than said radius of said core.

5. Transmission line as recited in claim **1** in which said first refractive index is substantially uniform in the radial direction from the center of said core.

6. Transmission line as recited in claim **1** in which said second refractive index is substantially uniform in the radial direction from the center of said core.

* * * * *

5/5

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(71) Applicant: **NIPPON TELEGRAPH AND TELEPHONE CORPORATION**
Shinjuku-ku, Tokyo 163-19 (JP)

(72) Inventors:
- **Kato, Masao, Nippon Telegr. & Teleph. Corp. Tokyo 163-14 (JP)**
- **Kurokawa, Kenji, Nippon Telegr. & Teleph. Corp. Tokyo 163-14 (JP)**
- **Horiguchi, Tuneo, Nippon Telegr. & Teleph. Corp. Tokyo 163-14 (JP)**
- **Miyajima, Yoshiaki, Nippon Telegr. & Teleph. Corp. Tokyo 163-14 (JP)**

(74) Representative: **Pfenning, Meinig & Partner**
Mozartstrasse 17
80336 München (DE)

(54) Optical fiber

(57) An optical fiber includes a core, a first cladding, a second cladding, and a third cladding. The core has a refractive index n_0. The first cladding is formed around the core and has a refractive index n_1. The second cladding is formed around the first cladding and has a refractive index n_2. The third cladding is formed around the second cladding and has a refractive index n_3. The refractive indices have relationships $n_1 > n_2 > n_3$ and $n_1 > n_0$.

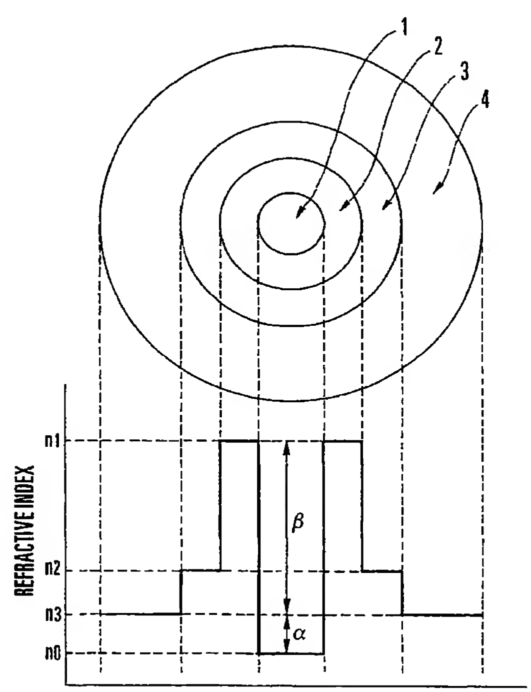


FIG. 1

EP 0 862 069 A2

Description

Background of the Invention

The present invention relates to an optical fiber.

A silica-based single-mode optical fiber (to be referred to as an SMF (Single-Mode Fiber) hereinafter) which is generally used in optical communication has a wavelength band for giving the minimum transmission loss within the range of 1.4 to 1.6 μm. Such a wavelength band is preferably used for long-distance optical communication. However, when an optical signal having the minimum transmission loss wavelength propagates through the SMF, the waveform degrades due to chromatic dispersion, resulting in limitations on the bit rate and the transmission distance.

The chromatic dispersion in such an optical fiber is given by both material dispersion and waveguide dispersion. For example, in a conventional SMF having a core diameter of 10 μm, whose relative index difference Δ between the core and cladding is 0.3%, material dispersion is more dominant than waveguide dispersion. Since the chromatic dispersion of silica used as a material is reflected to result in a zero-dispersion wavelength in the 1.3-μm band, the SMF used in a wavelength band of 1.5 μm of large-capacity optical communication has a chromatic dispersion of about +17 ps/nm/km.

Note that "+17 ps/nm/km" means that when an optical pulse having a spectral width of 1 nm (FWHM) propagates in a 1-km long optical fiber, the pulse width broadens by about 17 ps ("Nonlinear Fiber Optics", Govind P. Agrawal, p. 63 (Dispersion-induced Pulse Broadening), Academic Press).

Conventionally, demand has arisen for a technique of reducing the limitation on transmission capacity due to chromatic dispersion to increase the bit rate and transmission distance. To meet this requirement, an optical fiber called a dispersion shifted fiber (to be referred to as a DSF (Dispersion Shifted Fiber) hereinafter) has already been developed as an optical fiber having minimum chromatic dispersion in a communication wavelength band of 1.5 μm (Nobuo K. et al., "Characteristics of dispersion-shifted dual shape core single-mode fibers", J.L.T., LT-5, No. 6, p. 792 (1987)).

In this DSF, the index distribution of the core and cladding is designed such that waveguide dispersion has an opposite sign to that of material dispersion but the same absolute value. The zero-dispersion wavelength is set within the 1.5-μm band. To satisfy these conditions, the relative index difference Δ between the core and cladding is set to be 0.7% or more, i.e., the waveguide dispersion is made large. However, when the relative index difference Δ is large, the core diameter must be small to satisfy the single-mode condition (to be described later).

Consequently, the field distribution of light becomes narrow, and the effective core area (to be referred to as an Aeff hereinafter) is smaller than that of the SMF.

The single-mode condition will be described. In case of a step-index fiber, letting λ be the wavelength to be used, a normalized frequency V at the wavelength to be used is given by:

$$V = (2\pi/\lambda) \bullet a \bullet n_1 (2\Delta)^{0.5} \quad (1)$$

$$\Delta = (n_1 - n_2)/n_1 \quad (2)$$

where <u>a</u> is the core diameter, n_1 is the refractive index of the core, n_2 is the refractive index of the cladding, and Δ is the relative index difference between the core and cladding. To satisfy the single-mode condition, the value of the frequency V must be 2.405 or less.

When the relative index difference Δ is increased to make the waveguide dispersion large, the core diameter <u>a</u> must be designed to be small instead. However, when the core diameter <u>a</u> is reduced to increase the relative index difference Δ, the light confinement effect in the core increases. The Aeff becomes smaller than that of the SMF, and additionally, the bending loss decreases.

A transmission system with a regenerative repeater spacing of 320 km and a bit rate of 10 Gb/s has already been put into practical use by applying the DSF (Dispersion Shifted Fiber) to the transmission line and an erbium-doped optical fiber amplifier (to be referred to as an EDFA hereinafter) to the repeater device.

As a technique of increasing the transmission capacity, wavelength division multiplexing (to be referred to as WDM hereinafter) has conventionally received a great deal of attention domestically and internationally. With the WDM, a plurality of signal wavelengths can be simultaneously used in one communication optical fiber. This realizes a transmission system having a larger capacity than that of the conventional single wavelength transmission.

As described above, when the DSF is used as the transmission line, the intensity of light in the optical fiber (i.e., optical power per unit area of the fiber section) becomes high because of the small Aeff. On the other hand, along with the increase in intensity of signal light, phenomena called optical nonlinear effects are likely to take place in the optical fiber in general. Especially, the effects are easily induced in the DSF having a high intensity of light.

The optical nonlinear effect which decreases the S/N ratio is a serious problem because it imposes considerable limitations on the bit rate and transmission distance of the transmission system using the DSF. Therefore, an actual transmission system using the DSF must transmit signals while suppressing the gain of the optical amplifier.

However, as the bit rate rises, the time slot per signal bit becomes short. To ensure the received power lev-

el, signal power per bit must be increased. This does not agree with suppression of optical nonlinear effects. To suppress the optical nonlinear effects, transmission power must be reduced to limit the bit rate.

When the WDM is employed to increase the transmission capacity, optical nonlinear effects called four-wave mixing (to be referred to as FWM hereinafter) are induced because of presence of a plurality of wavelengths in the optical fiber, so the bit rate and transmission distance are limited.

In the FWM, the third-order nonlinear optical process causes interference between signal wavelengths to generate new light. As the phase matching condition between wavelengths is satisfied, the FWM generation efficiency increases. For this reason, the FWM is more likely to take place when the signal wavelengths are closer to the zero-dispersion wavelength, and the interval between signal wavelengths is smaller. In the DSF whose zero-dispersion wavelength is within the signal wavelength band, the FWM is more likely to be induced than in the SMF, so the interval between signal wavelengths must be increased. However, since the amplification bandwidth of the EDFA is about several ten nm, a large wavelength interval decreases the number of signal channels to limit the transmission capacity.

The application purpose of the DSF is not limited to the transmission line.

For the further improvement of the transmission system, extensive studies on a high-speed optical switch and wavelength conversion device have also been made. The optical switch and wavelength conversion device perform switching or wavelength conversion using the optical nonlinear effects, unlike the transmission line, so how to induce the optical nonlinear effects is the important problem.

An optical switch and wavelength conversion device which are realized using the DSF in which the optical nonlinear effects readily occur because of the small Aeff have already been reported.

However, at a bit rate of 20 Gb/s or more, electrical signal processing cannot be used, and instead, the optical switch or wavelength conversion device must be used. The DSF to be used for the optical switch or wavelength conversion device must have a length of several ten km because the conversion efficiency is low. In addition, input optical power is required.

Summary of the Invention

It is, therefore, a principal object of the present invention to provide an optical fiber allowing easy design of suppression and enhancement of optical nonlinear effects.

It is another object of the present invention to provide an optical fiber capable of suppressing optical nonlinear effects by lowering the intensity of light in the optical fiber, and suppressing FWM by disturbing the phase matching condition between wavelengths.

It is still another object of the present invention to provide an optical fiber capable of enhancing optical nonlinear effects by increasing the intensity of light in the optical fiber.

In order to achieve the above objects of the present invention, there is provided an optical fiber comprising a core having a refractive index n_0, a first cladding formed around the core and having a refractive index n_1, a second cladding formed around the first cladding and having a refractive index n_2, and a third cladding formed around the second cladding and having a refractive index n_3, wherein the refractive indices have relationships $n_1 > n_2 > n_3$ and $n_1 > n_0$.

With this arrangement, an optical fiber capable of suppressing or enhancing the optical nonlinear effects can be provided. An optical fiber for suppressing the optical nonlinear effects can be used for a transmission line. An optical fiber for inducing the optical nonlinear effects can be used for an optical switch or wavelength conversion device.

Brief Description of the Drawings

Fig. 1 is a view showing the section of an optical nonlinearity suppressing fiber according to the present invention and its index distribution;
Fig. 2 is a graph showing the relationship between chromatic dispersion and a relative index difference a between a core and a third cladding;
Fig. 3 is a graph showing the relationship between chromatic dispersion and a relative index difference β between a first cladding and the third cladding;
Fig. 4 is a graph showing the relationship between the second cladding diameter and chromatic dispersion;
Figs. 5A, 5B, and 5C are graphs showing the relationships between the fiber length and chromatic dispersion;
Fig. 6 is a view showing the arrangement of a transmission line using the optical nonlinearity suppressing fiber shown in Fig. 1 and the relationship between the transmission distance and the optical power level;
Fig. 7 is a view showing the section of an optical nonlinearity suppressing fiber according to the present invention and its index distribution;
Figs. 8A and 8B are graphs showing the relationship between the MFD and the relative index difference a between the core and the third cladding;
Fig. 9 is a graph showing the relationship between the MFD and the ratio of the core diameter to the first cladding diameter;
Fig. 10 is a graph showing the relationship between the chromatic dispersion variation and the FWM generation efficiency;
Fig. 11 is a graph showing the relationship between the fiber length and chromatic dispersion;
Fig. 12 is a graph showing the relationship between

the core diameter and the relative index difference β between the first cladding and the third cladding;
Fig. 13 is a graph showing the relationship between the Aeff and the relative index difference β between the first cladding and the third cladding;
Fig. 14 is a graph showing the relationship between the wavelength and chromatic dispersion; and
Fig. 15 is a graph showing the relationship between the bending radius and the bending loss.

Detailed Description of the Preferred Embodiment

An embodiment of the present invention will be described next with reference to the accompanying drawings.

First, an optical fiber (to be referred to as an optical nonlinearity suppressing fiber hereinafter) which can be used for a transmission line by suppressing optical nonlinear effects will be described.

Fig. 1 shows the section of the optical nonlinearity suppressing fiber and its index distribution. As shown in Fig. 1, to suppress the optical nonlinear effects, the refractive index at the core center of a DSF is lowered. More specifically, the optical fiber of this embodiment is formed from a core 1 having a refractive index n_0, a cladding 2 (to be referred to as a first cladding hereinafter) having a refractive index n_1, a cladding 3 (to be referred to as a second cladding hereinafter) having a refractive index n_2, and a cladding 4 (to be referred to as a third cladding hereinafter) having a refractive index n_3, and the refractive indices have at least relationships $n_1 > n_2 > n_3$ and $n_1 > n_0$. Especially, in this case, to suppress the optical nonlinear effects, the refractive indices are set such that a relationship $n_1 > n_2 > n_3 > n_0$ is established. With this arrangement, the first cladding effectively functions as a core. The field distribution of light spreads in the radial direction of the optical fiber to increase the Aeff, so the optical nonlinear effects can be suppressed.

Such an optical nonlinearity suppressing fiber is made of the same material (e.g., silica) as that of the conventional optical fiber although the intensity of light lowers, so the optical nonlinearity suppressing fiber can be spliced to the conventional transmission line. Therefore, optical power in the transmission line can be increased, and simultaneously, degradation in transmission due to the optical nonlinear effects can be suppressed by inserting this fiber immediately after the optical amplifier in which the optical nonlinear effects readily occur.

However, as described above, when WDM is employed to increase the transmission capacity, optical nonlinear effects called FWM take place because of presence of a plurality of wavelengths in the optical fiber, resulting in limitations on the bit rate and transmission distance.

The FWM is suppressed by varying chromatic dispersion of the optical fiber along the longitudinal direction. More specifically, when chromatic dispersion varies along the longitudinal direction of the optical fiber, phase velocity of light locally changes in the transmission line. For this reason, in WDM transmission, the phase matching condition between adjacent channels is disturbed, so FWM as a limitation factor on transmission can be suppressed.

Some methods are available to vary chromatic dispersion. For example, when a relative index difference α between the core and the third cladding is continuously changed along the longitudinal direction in the manufacture of the optical fiber, chromatic dispersion at 1.55 µm can be continuously varied.

Fig. 2 shows a change in chromatic dispersion at 1.55 µm when the relative index difference α between the core and third cladding of the optical fiber shown in Fig. 1 is changed. A relative index difference β between the first and third claddings is 1.5%.

The relative index difference α is given by:

$$\alpha = (n_0 - n_3)/n_0$$

The relative index difference β is given by:

$$\beta = (n_1 - n_3)/n_1$$

The optical fiber shown in Fig. 2, whose chromatic dispersion varies from +12 ps/nm/km to -12 ps/nm/km (chromatic dispersion variation: 24 ps/nm/km), is merely an example for explaining the chromatic dispersion variation obtained upon changing the relative index difference α from, e.g., 0% to -0.4%, so the chromatic dispersion value need not always be ±12 ps/nm/km.

Even when the relative index difference β between the first cladding and the third cladding is changed, chromatic dispersion at 1.55 µm can be continuously changed. Fig. 3 shows a change in chromatic dispersion at 1.55 µm observed upon changing the relative index difference β. The relative index difference α is -0.4%.

The chromatic dispersion can also be varied by changing the second cladding diameter along the longitudinal direction of the optical fiber. Fig. 4 shows a change in chromatic dispersion at 1.55 µm observed upon-changing the second cladding diameter. The relative index difference α is -0.4%, and the relative index difference β is 1.44%.

Figs. 5A to 5C show the relationships between the fiber length and chromatic dispersion obtained when the relative index differences α and β and the second cladding diameter are changed. In Fig. 5A, the wavelength is 1.55 µm, and the relative index difference β is 1.5%. In Fig. 5B, the wavelength is 1.55 µm, and the relative index difference α is -0.4%. In Fig. 5C, the wavelength is 1.55 µm, the relative index difference α is -0.4%, and the relative index difference β is 1.44%.

In all cases, chromatic dispersion continuously low-

ers as the fiber length increases, and the chromatic dispersion changes depending on the position in the optical fiber, as is apparent from Figs. 5A to 5C. Alternatively, the phase matching condition may be disturbed to suppress FWM by periodically changing both the relative index difference α between the core and third cladding and the relative index difference β between the first and third claddings along the longitudinal direction in the manufacture of the optical fiber.

The above-described optical nonlinearity suppressing fiber may be used in the following manner.

Fig. 6 shows the arrangement of the transmission line using the optical fiber shown in Fig. 1 and the relationship between the transmission distance and optical power level. As shown in Fig. 6, a transmitter 5 comprises a light source 5a and an optical amplifier 5b. A receiver 7 comprises a detector 7a and an optical amplifier 7b. An optical amplifier 6 is inserted between the transmitter 5 and the receiver 7. The transmitter 5 and the receiver 7 are connected through the optical amplifier 6, an optical nonlinearity suppressing fiber 8, and a conventional optical fiber 9.

This arrangement is based on the following reason. An actual optical fiber always has a transmission loss, optical power of an optical signal gradually becomes small during transmission. That is, the optical nonlinear effects are most conspicuous at positions (A and B in Fig. 6) immediately after optical amplifiers in the optical fiber transmission line. Therefore, when the optical nonlinearity suppressing fiber shown in Fig. 1 is inserted immediately after the optical amplifier in the conventional transmission line, the optical nonlinear effects can be effectively suppressed.

An optical fiber (to be referred to as an optical nonlinearity enhancing fiber hereinafter) which can be used for an optical switch or wavelength conversion device by inducing the optical nonlinear effects will be described next.

Fig. 7 shows the section of the optical nonlinearity enhancing fiber and its index distribution. As shown in Fig. 7, the refractive index n_0 of the core is made higher than the refractive index n_3 of the third cladding and lower than the refractive index n_1 of the first cladding to strengthen the light confinement effect at the center of the optical fiber, and the Aeff is reduced, thereby inducing the optical nonlinear effects (i.e., $n_1 > n_2 > n_3$, and $n_1 > n_0 > n_3$). With this arrangement, the intensity of light in the optical fiber becomes high. The optical nonlinear effects occur in accordance with the product of the intensity of light (power) and the nonlinear length, so this optical fiber can induce the optical nonlinear effects at a high efficiency.

Examples of the present invention will be described next.

Figs. 8A and 8B show a change in mode field diameter (to be referred to as an MFD hereinafter) when the relative index difference α between the core and the third cladding is changed.

The MFD is a parameter indicating the extension of field distribution of light in the fiber and is known to be proportional to the Aeff (Namihira et al., "Nonlinear Kerr Coefficient Measurements for Dispersion Shifted Fibers using Self-Phase Modulation Method at 1.55 μm", OEC '94).

As shown in Fig. 8A, when the absolute value of the relative index difference α is increased in the negative direction, the field distribution of light spreads to lower the intensity, so the optical fiber of this embodiment becomes the optical nonlinearity suppressing fiber for suppressing the optical nonlinear effects. From the viewpoint of manufacturing, the dose of fluorine which is doped to lower the refractive index of the core is limited, so the relative index difference α has its lower limit value within the range of -0.7% to -0.8% in fact.

On the other hand, as shown in Fig. 8B, when the relative index difference α is increased to the positive direction, the value of MFD becomes small. MFD of a general dual-shaped dispersion shifted fiber is effectively about 7.4 to 8.4 μm (Aeff = 41 to 53 μm^2). With the relative index difference *a* having a positive value, the field distribution becomes narrower than that of the DSF, and the intensity of light rises, so the optical nonlinearity enhancing fiber is obtained.

If the electric field has a Gaussian distribution, Aeff $= \pi \times (MFD/2)^2$ is obtained. When MFD increases, the Aeff also increases. However, if the optical fiber of the present invention is formed as the optical nonlinearity suppressing fiber (i.e., $\alpha < 0$), the field distribution deviates from the Gaussian distribution, so the right-hand side of the above equation must be multiplied by a correction coefficient c ($c > 1$).

Fig. 9 shows a change in MFD observed when the ratio of the core diameter to the first cladding diameter is changed. In Fig. 9, a bullet indicates a value when the relative index difference α between the core and third cladding is 0%; and a hollow bullet, a value when the relative index difference α is +0.3%. As shown in Fig. 9, when the relative index difference *a* is 0%, and the ratio of the core diameter to the first cladding diameter is 0.4 or less, MFD becomes smaller than that of the DSF. Since the intensity of light rises, the optical nonlinearity enhancing fiber is obtained. When the relative index difference α is +0.3%, and the ratio of the core diameter to the first cladding diameter is 0.5 or less, the optical nonlinearity enhancing fiber is expected to be obtained.

The FWM suppressing effect will be described next.

Fig. 10 shows the FWM suppressing effect. As is apparent from Fig. 10, FWM can be suppressed by changing chromatic dispersion along the longitudinal direction of the optical fiber.

Fig. 10 shows the dependence of the FWM generation efficiency (normalized by defining the generation efficiency for a dispersion variation of 0 as 1) in a chromatic-dispersion varying fiber (length: 40 km), whose chromatic dispersion linearly increases along the longitudinal direction of the optical fiber, on the chromatic dis-

persion variation (chromatic dispersion difference between the input side and output side) (Fig. 11).

When the chromatic dispersion variation is 4 ps/nm/km, the FWM generation efficiency is 1/10 that of the normal optical fiber whose chromatic dispersion variation is 0, or less, so a sufficient suppressing effect can be obtained. The suppressing effect can be increased by increasing the chromatic dispersion variation. In addition, as is apparent from Fig. 10, the FWM generation efficiency can be suppressed to about 0.03 with a chromatic dispersion variation of 20 ps/nm/km. For a chromatic dispersion variation of 24 ps/nm/km, a larger FWM suppressing effect is expected.

Fig. 12 shows the relationship between the core diameter for satisfying the single-mode condition and the relative index difference β between the first and third claddings when the relative index difference α between the core and the third cladding is changed. The hatched portion in Fig. 12 indicates a region where the single-mode condition cannot be satisfied at 1.55 μm. As the relative index difference α becomes small, the number of combinations of the core diameter and relative index difference β for satisfying the single-mode condition increases.

In an optical fiber shown in Fig. 13, the Aeff could be increased to about 150 μm^2 at a zero-dispersion wavelength of 1.55 μm by setting the relative index difference α at about -0.3% and relative index difference β at about 1%. Fig. 14 shows a change in zero-dispersion wavelength when each relative index difference is changed while maintaining the index relationships $n_1 > n_2 > n_3$ and $n_1 > n_0$. As is apparent from Fig. 14, zero dispersion in the wavelength band of 1.4 to 1.5 μm is realized. By changing the combination of relative index differences, zero dispersion in the wavelength band of 1.3 to 1.6 μm or in a longer wavelength band can also be realized.

Considering the handling characteristics of the above-described optical fiber in actual use for a transmission line or the like, the optical fiber must have a small bending loss. The optical fiber of this embodiment could improve its bending loss characteristics by increasing the relative index difference β. Fig. 15 shows the bending loss characteristics with respect to the bending radius of the optical fiber of this embodiment. As is apparent from Fig. 15, the bending loss decreases as the relative index difference β increases. In addition, the optical fiber of this embodiment can obtain almost the same bending loss characteristics as those of the conventional DSF (about several dB/m for a bending radius of 1 cm; Aeff is about 50 μm^2) by setting the relative index difference β at about 1.5%. In this case, the Aeff is about 120 μm^2.

According to the optical fiber of the present invention, even when the zero-dispersion wavelength is designed in a band of 1.55 μm, the field distribution does not concentrate to the center of the optical fiber. For this reason, the Aeff can be made larger than that of the conventional DSF by twice or more while maintaining almost the same bending loss characteristics. More specifically, the intensity of light lowers to suppress the optical nonlinear effects, and consequently, degradation in signal waveform is suppressed, so the bit rate and transmission distance can be increased.

In addition, when the phase matching condition between wavelengths is disturbed by changing the zero-dispersion wavelength in a band of 1.55 μm along the longitudinal direction of the optical fiber, the FWM generation efficiency can be lowered. Therefore, the wavelength interval in WDM can be reduced to increase the number of channels.

On the other hand, when the Aeff is decreased, the intensity of light in the optical fiber can be made high. Since the optical nonlinear effects can be efficiently generated, an optical fiber suitable for an optical switch or wavelength conversion device can be provided.

Claims

1. An optical fiber characterized by comprising:

   a core (1) having a refractive index n_0;
   a first cladding (2) formed around said core and having a refractive index n_1;
   a second cladding (3) formed around said first cladding and having a refractive index n_2; and
   a third cladding (4) formed around said second cladding and having a refractive index n_3,
   wherein the refractive indices have relationships $n_1 > n_2 > n_3$ and $n_1 > n_0$.

2. A fiber according to claim 1, wherein the refractive indices further have a relationship $n_3 \geq n_0$.

3. A fiber according to claim 1, wherein the refractive indices further have a relationship $n_0 > n_3$.

4. A fiber according to claim 2, wherein a relative index difference α between said core and said third cladding continuously changes along a longitudinal direction of said optical fiber.

5. A fiber according to claim 3, wherein a relative index difference α between said core and said third cladding continuously changes along a longitudinal direction of said optical fiber.

6. A fiber according to claim 2, wherein a relative index difference β between said first cladding and said third cladding continuously changes along a longitudinal direction of said optical fiber.

7. A fiber according to claim 3, wherein a relative index difference β between said first cladding and said third cladding continuously changes along a longi-

tudinal direction of said optical fiber.

8. A fiber according to claim 2, wherein a diameter of said second cladding continuously changes along a longitudinal direction of said optical fiber.

9. A fiber according to claim 3, wherein a diameter of said second cladding continuously changes along a longitudinal direction of said optical fiber.

10. A fiber according to claim 4, wherein the relative index difference α between said core and said third cladding monotonically increases or monotonically decreases along the longitudinal direction of said optical fiber.

11. A fiber according to claim 5, wherein the relative index difference α between said core and said third cladding monotonically increases or monotonically decreases along the longitudinal direction of said optical fiber.

12. A fiber according to claim 6, wherein the relative index difference β between said first cladding and said third cladding monotonically increases or monotonically decreases along the longitudinal direction of said optical fiber.

13. A fiber according to claim 7, wherein the relative index difference β between said first cladding and said third cladding monotonically increases or monotonically decreases along the longitudinal direction of said optical fiber.

14. A fiber according to claim 8, wherein the diameter of said second cladding monotonically increases along the longitudinal direction of said optical fiber.

15. A fiber according to claim 8, wherein the diameter of said second cladding monotonically decreases along the longitudinal direction of said optical fiber.

16. A fiber according to claim 9, wherein the diameter of said second cladding monotonically increases along the longitudinal direction of said optical fiber.

17. A fiber according to claim 9, wherein the diameter of said second cladding monotonically decreases along the longitudinal direction of said optical fiber.

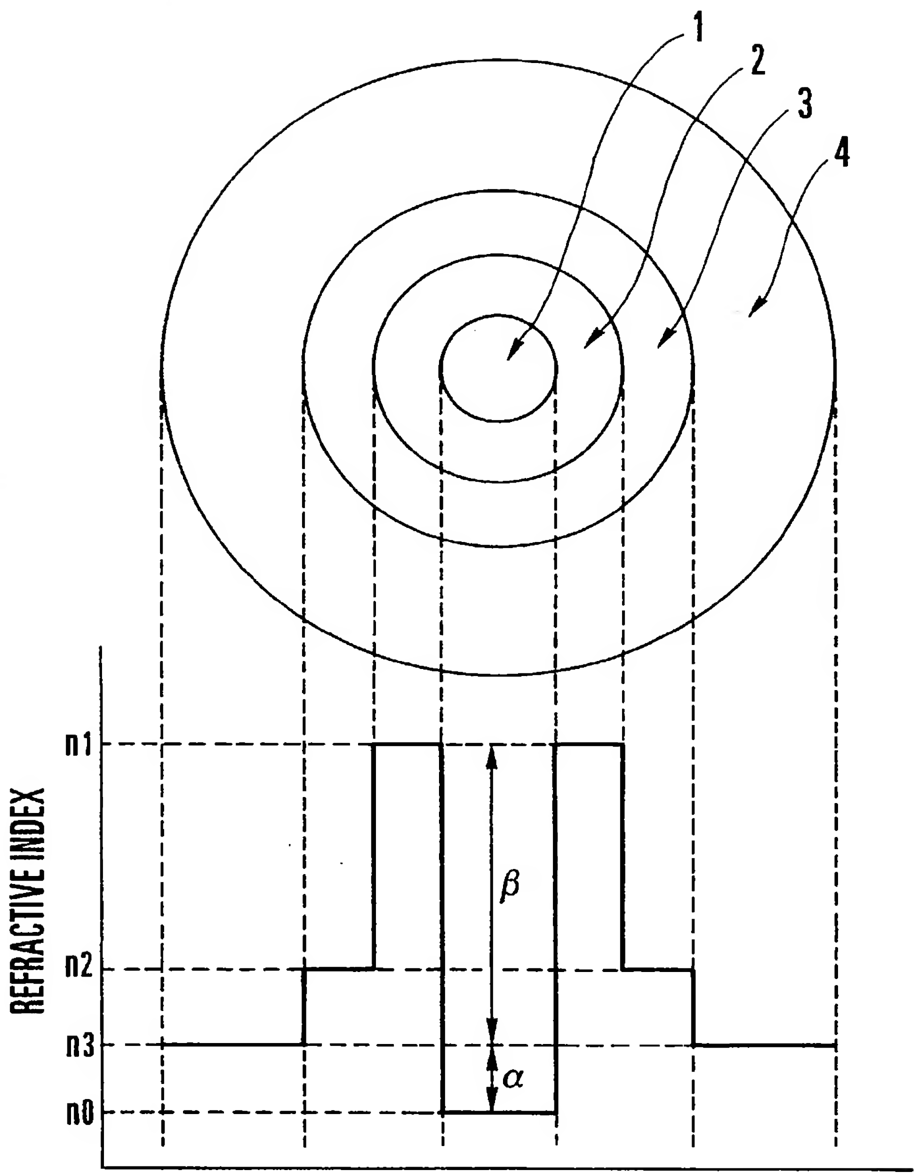


FIG. 1

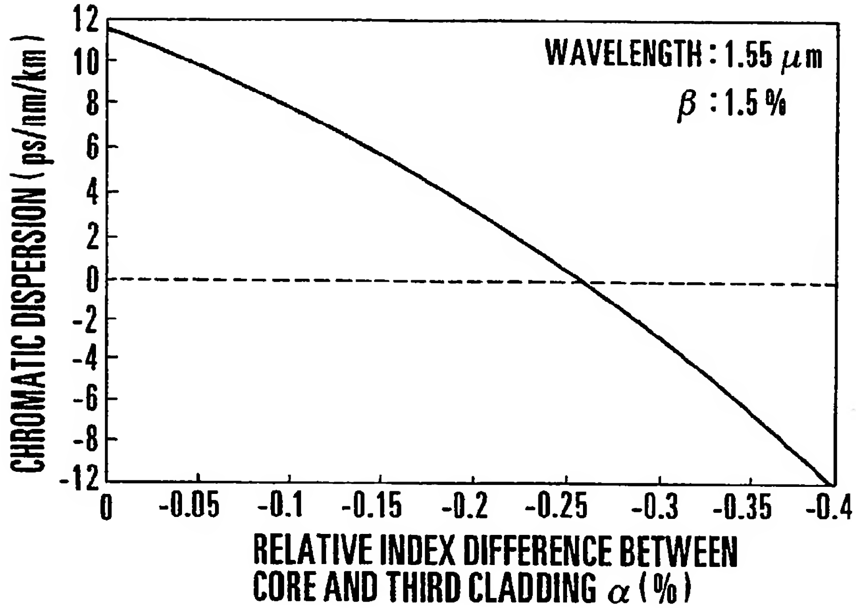

WAVELENGTH : 1.55 μm
β : 1.5 %
CHROMATIC DISPERSION (ps/nm/km)
12
10
8
6
4
2
0
-2
-4
-6
-8
-12
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
-0.4
RELATIVE INDEX DIFFERENCE BETWEEN
CORE AND THIRD CLADDING α (%)

FIG. 2

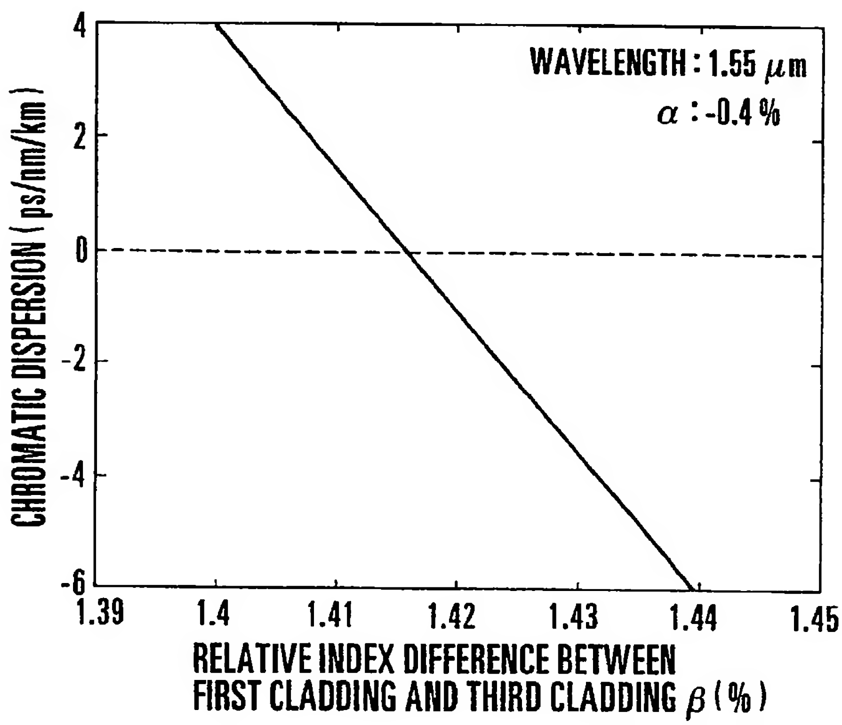
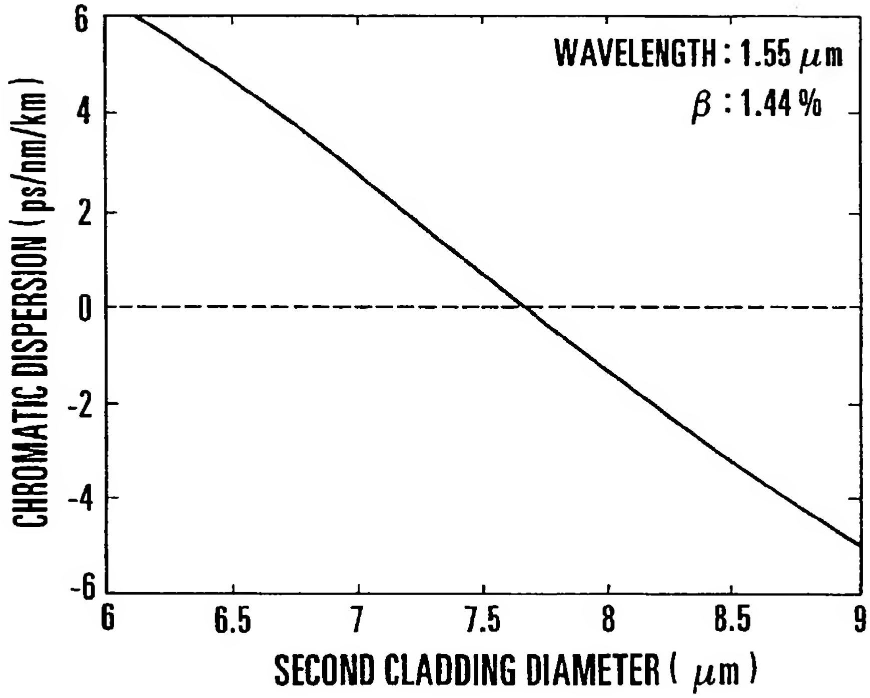

WAVELENGTH : 1.55 μm
α : -0.4 %
CHROMATIC DISPERSION (ps/nm/km)
4
2
0
-2
-4
-6
1.39
1.4
1.41
1.42
1.43
1.44
1.45
RELATIVE INDEX DIFFERENCE BETWEEN
FIRST CLADDING AND THIRD CLADDING β (%)

FIG. 3



6
4
2
0
-2
-4
-6
CHROMATIC DISPERSION (ps/nm/km)
6
6.5
7
7.5
8
8.5
9
SECOND CLADDING DIAMETER (μm)
WAVELENGTH : 1.55 μm
β : 1.44 %

FIG. 4

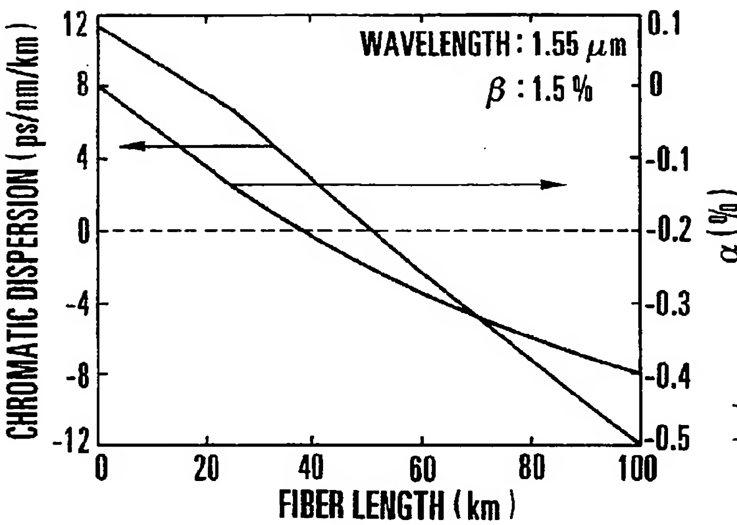


FIG.5A

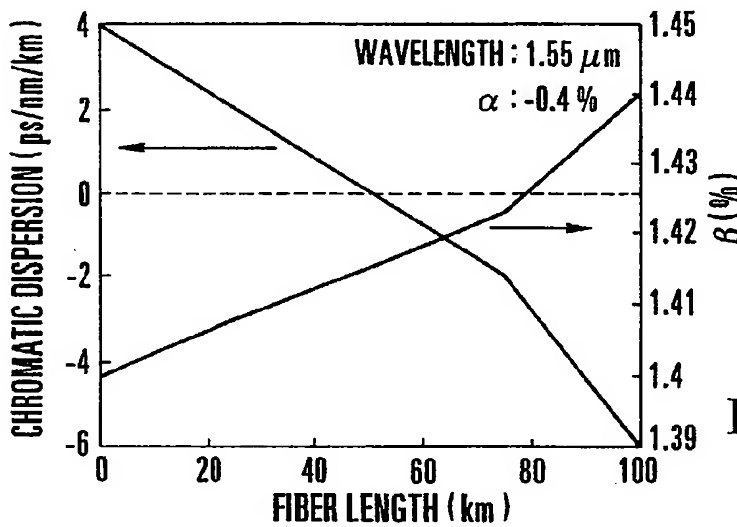


FIG.5B

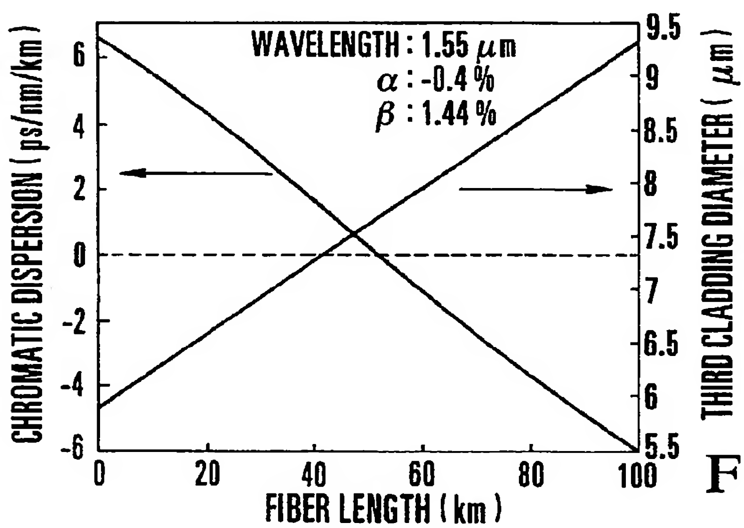


FIG.5C

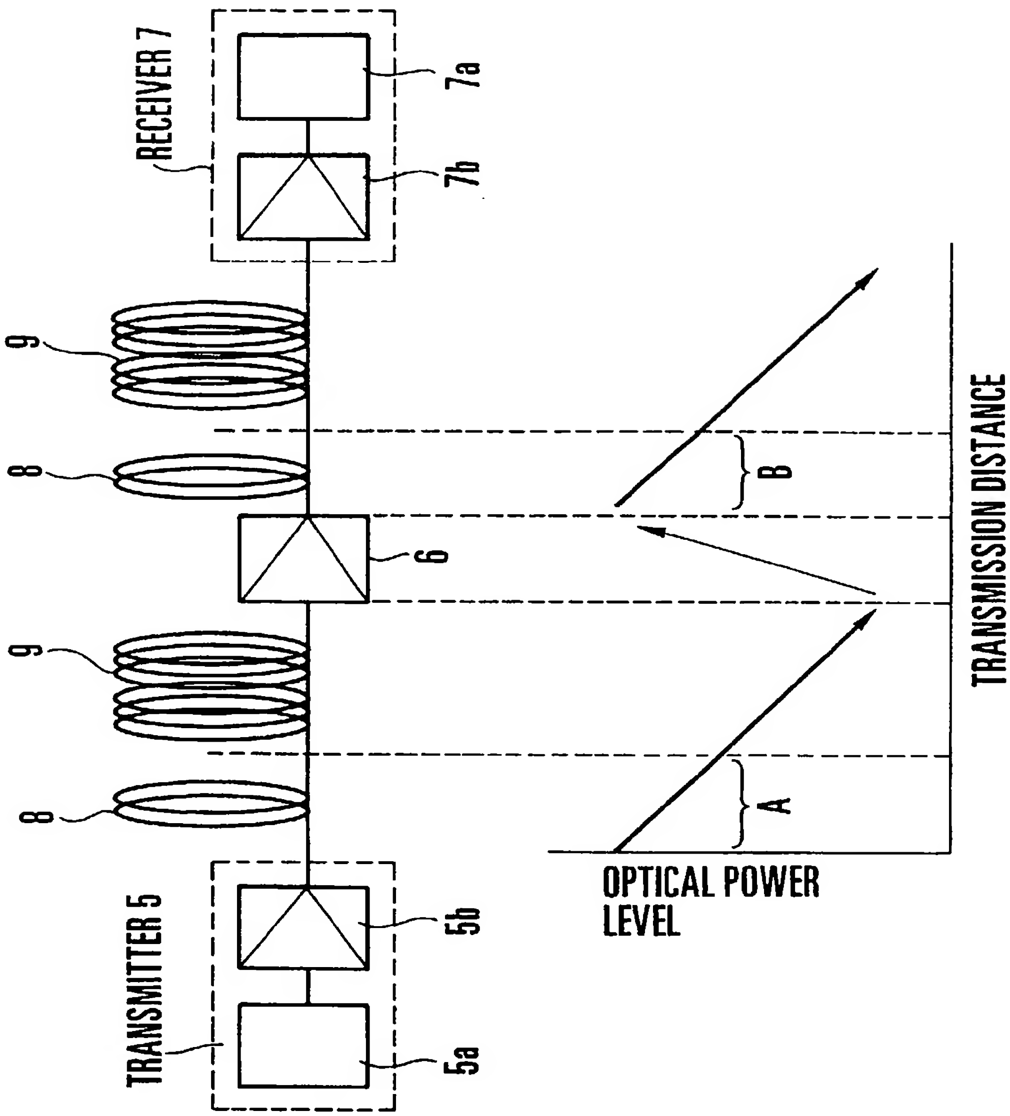

TRANSMITTER 5
5a
5b
8
9
8
6
9
RECEIVER 7
7b
7a
OPTICAL POWER LEVEL
A
B
TRANSMISSION DISTANCE

FIG.6

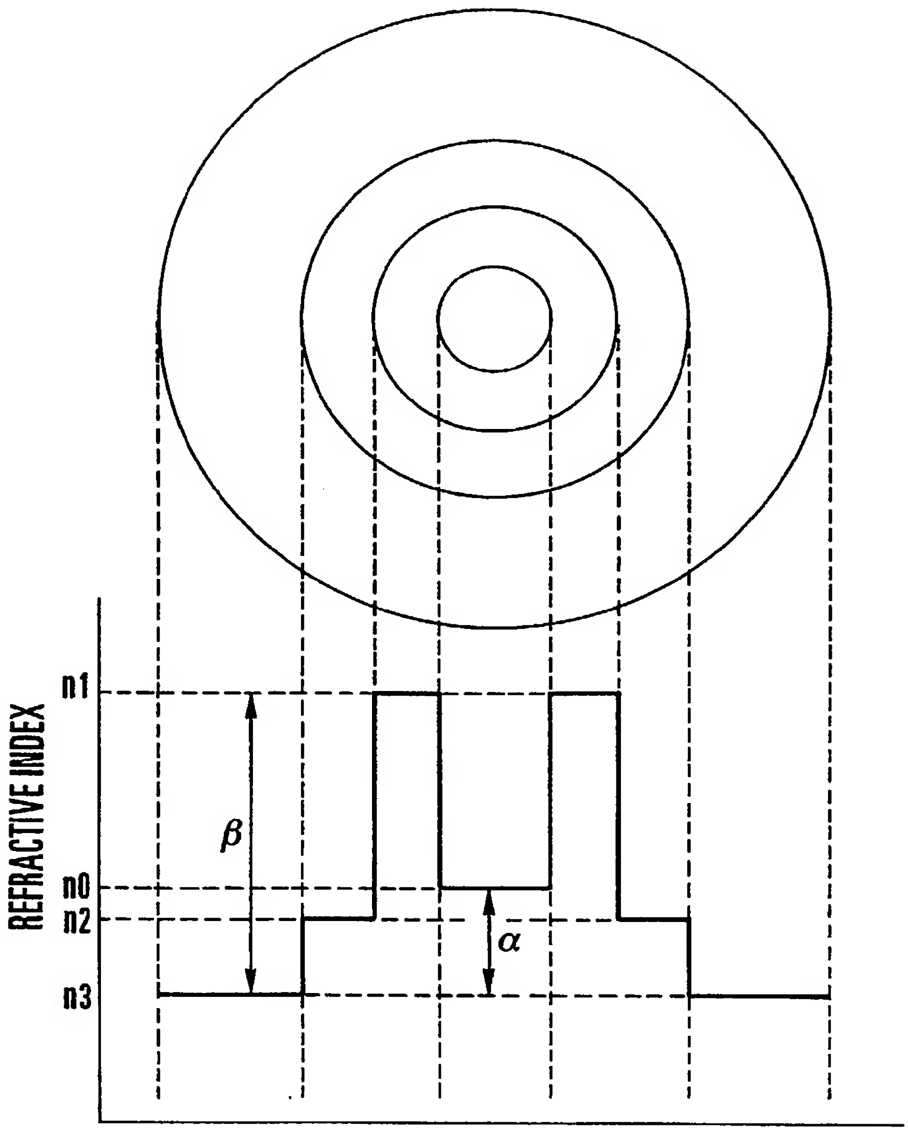


FIG.7

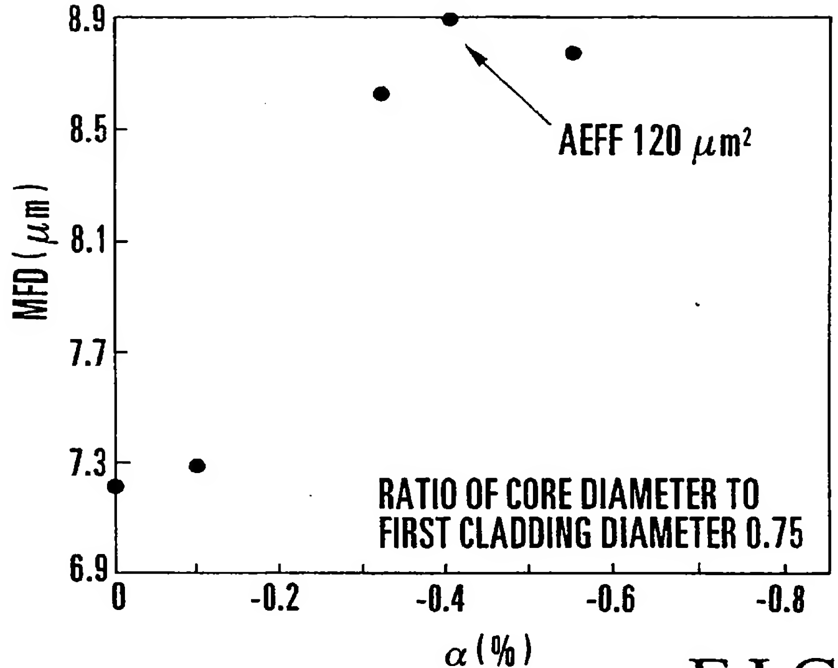

8.9
8.5
8.1
7.7
7.3
6.9
MFD (μm)
AEFF 120 μm²
RATIO OF CORE DIAMETER TO
FIRST CLADDING DIAMETER 0.75
0
-0.2
-0.4
-0.6
-0.8
α (%)

FIG. 8A

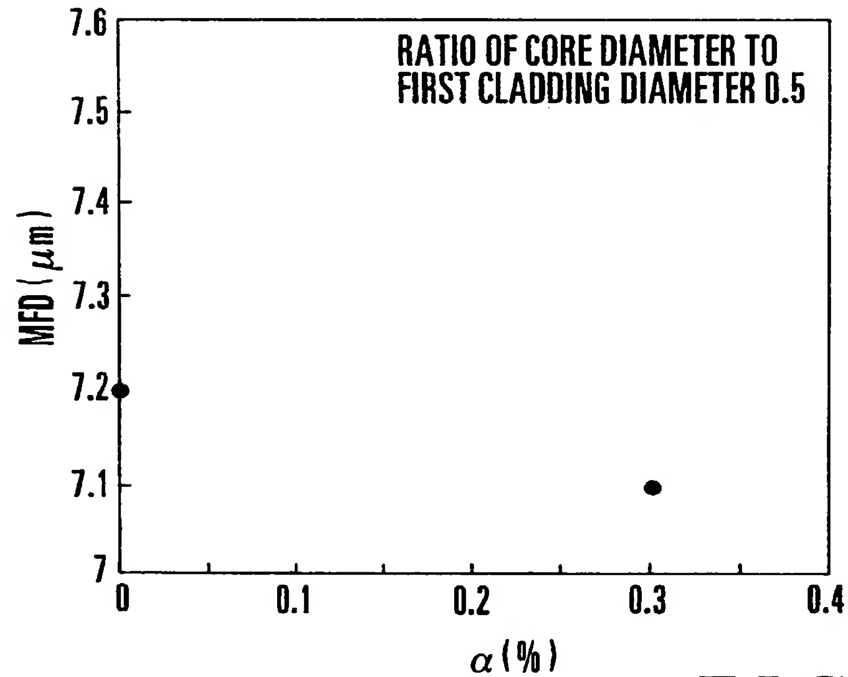

7.6
7.5
7.4
7.3
7.2
7.1
7
MFD (μm)
RATIO OF CORE DIAMETER TO
FIRST CLADDING DIAMETER 0.5
0
0.1
0.2
0.3
0.4
α (%)

FIG. 8B

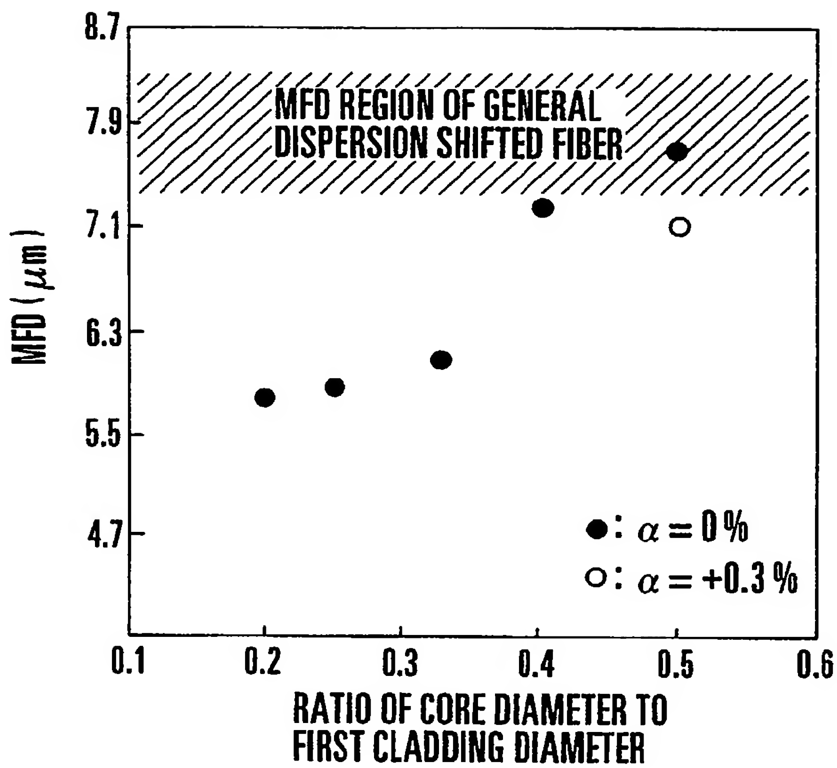
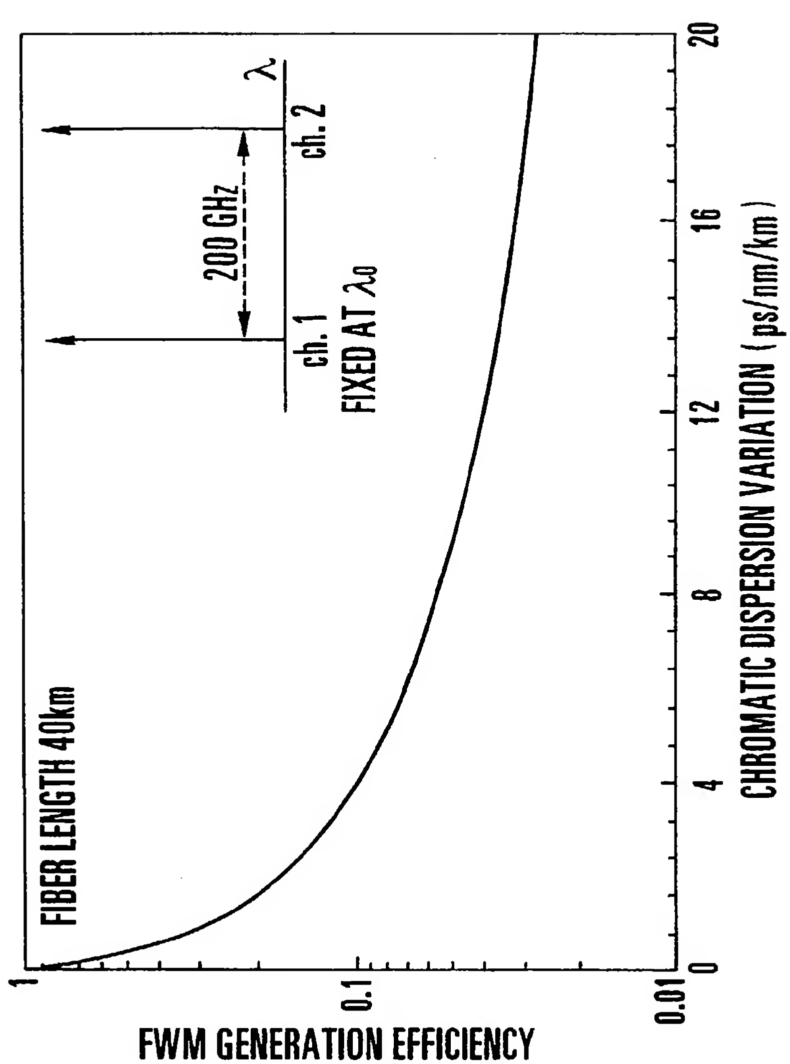
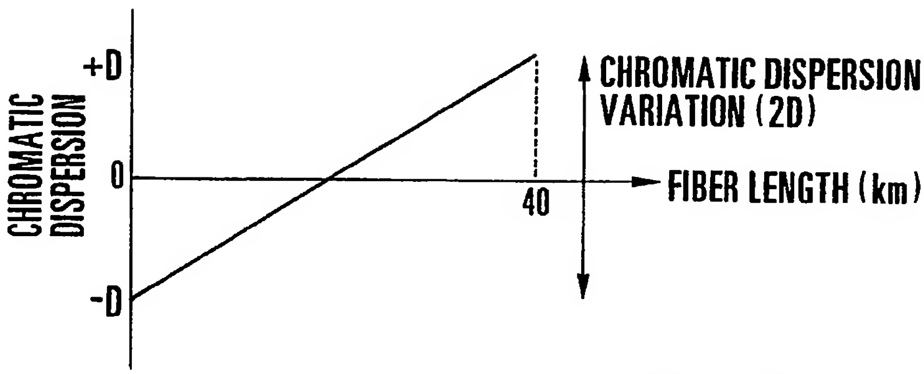

8.7
7.9
7.1
6.3
5.5
4.7
MFD (μm)
MFD REGION OF GENERAL
DISPERSION SHIFTED FIBER
●: α = 0 %
○: α = +0.3 %
0.1
0.2
0.3
0.4
0.5
0.6
RATIO OF CORE DIAMETER TO
FIRST CLADDING DIAMETER

FIG. 9

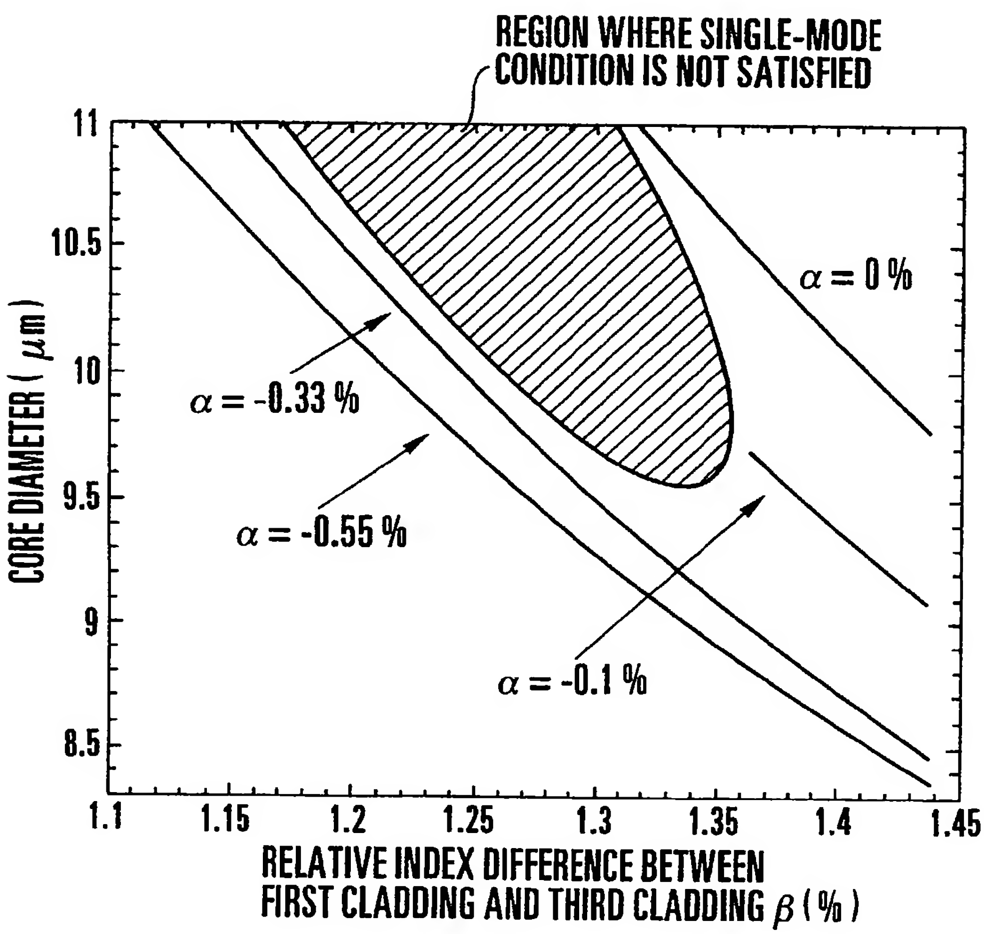


FIBER LENGTH 40km
200 GHz
ch. 1
ch. 2
λ
FIXED AT λ_0
FWM GENERATION EFFICIENCY
1
0.1
0.01
0
4
8
12
16
20
CHROMATIC DISPERSION VARIATION (ps/nm/km)

F I G. 10


CHROMATIC DISPERSION
+D
0
-D
40
CHROMATIC DISPERSION VARIATION (2D)
FIBER LENGTH (km)

F I G. 11


REGION WHERE SINGLE-MODE CONDITION IS NOT SATISFIED
CORE DIAMETER (μm)
11
10.5
10
9.5
9
8.5
1.1
1.15
1.2
1.25
1.3
1.35
1.4
1.45
α = 0 %
α = -0.33 %
α = -0.55 %
α = -0.1 %
RELATIVE INDEX DIFFERENCE BETWEEN FIRST CLADDING AND THIRD CLADDING β (%)

F I G. 12

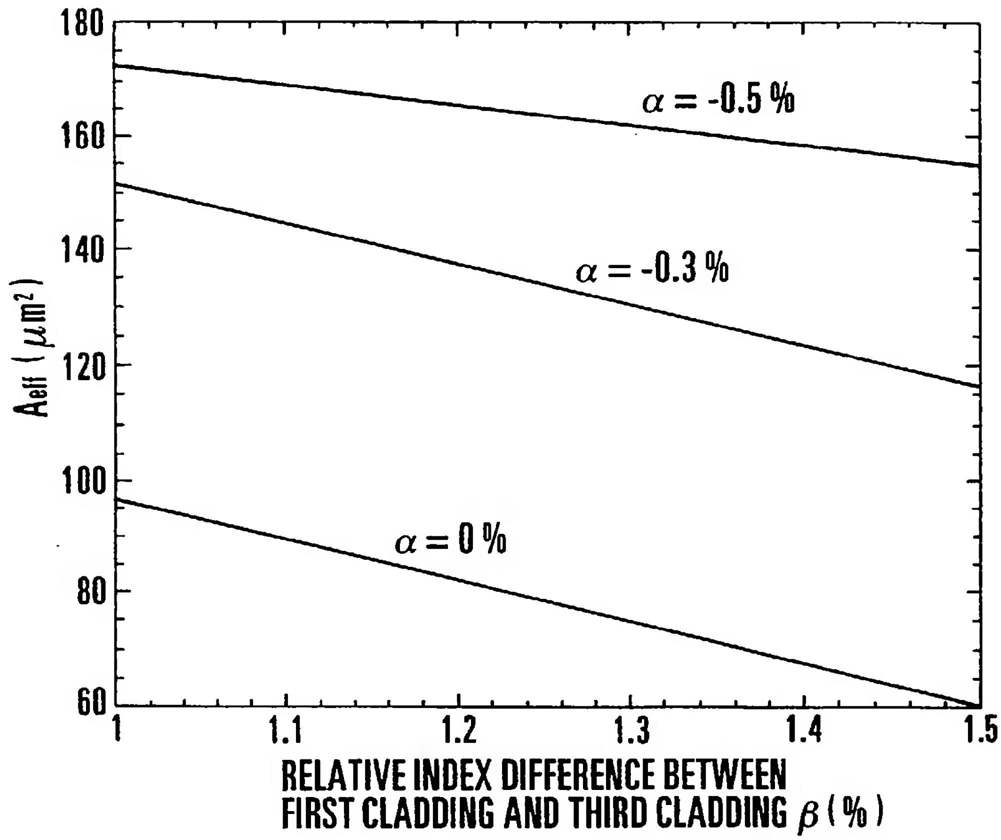

180
160
140
120
100
80
60
Aeff (μm²)
α = -0.5 %
α = -0.3 %
α = 0 %
1
1.1
1.2
1.3
1.4
1.5
RELATIVE INDEX DIFFERENCE BETWEEN
FIRST CLADDING AND THIRD CLADDING β (%)

FIG. 13

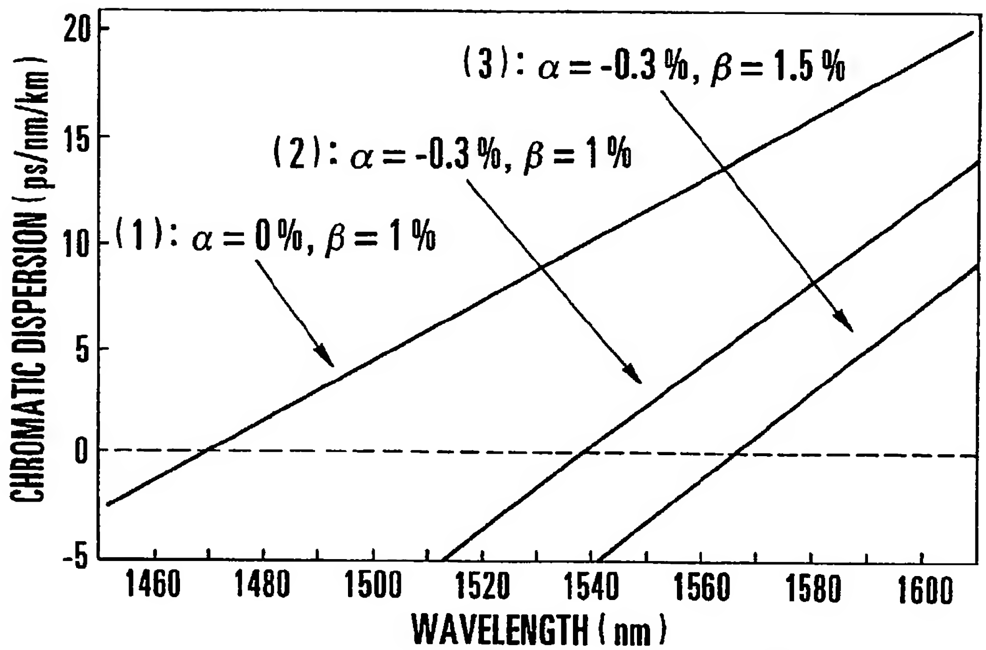

CHROMATIC DISPERSION (ps/nm/km)
WAVELENGTH (nm)
(1): α = 0 %, β = 1 %
(2): α = -0.3 %, β = 1 %
(3): α = -0.3 %, β = 1.5 %
20
15
10
5
0
-5
1460
1480
1500
1520
1540
1560
1580
1600

FIG. 14

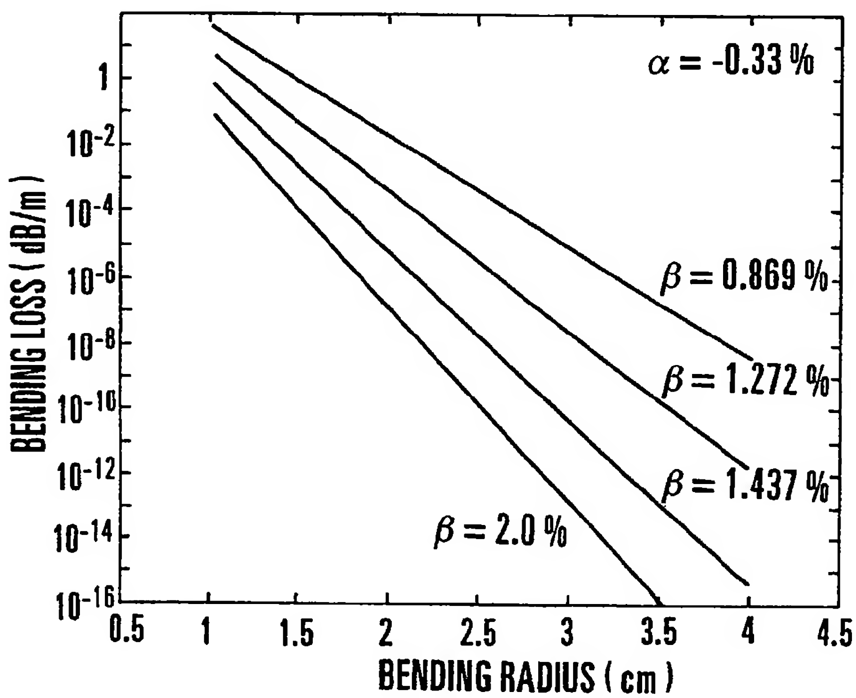

BENDING LOSS (dB/m)
BENDING RADIUS (cm)
α = -0.33 %
β = 0.869 %
β = 1.272 %
β = 1.437 %
β = 2.0 %
1
10-2
10-4
10-6
10-8
10-10
10-12
10-14
10-16
0.5
1
1.5
2
2.5
3
3.5
4
4.5

FIG. 15